CRC Report No. AVFL-17

INVESTIGATION OF BIODISTILLATES AS POTENTIAL BLENDSTOCKS FOR TRANSPORTATION FUELS

June, 2009



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CRC Project No. AVFL-17 Final Report

Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels

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Executive Summary

The AVFL-17 Project was initiated by CRC to assess the state-of-knowledge regarding biofuels as blending materials for ultra-low sulfur diesel (ULSD) fuel in transportation applications. Topics investigated include policy drivers, biofuel feedstocks, fuel production technologies, fuel properties and specifications, in-use handling and performance, exhaust emissions effects, and life-cycle impacts. Data gaps were identified and areas for further work were recommended.

The comprehensive term, biodistillate, is used to include all plant- and animal-derived middle distillate fuels intended for diesel engines, regardless of the production technology used to manufacture the fuels. The two major biodistillate categories are: (1) biodiesel [such as fatty acid methyl esters (FAME) produced via transesterification of animal fats and vegetable oils] and (2) renewable diesel (produced via catalytic hydroprocessing of the same feedstocks). Other terms such as "1st Generation" and "2nd Generation" fuels are commonly used, but have variable meanings. In this study, conventional biodiesel (FAME) is regarded as 1st Generation, while hydroprocessed renewable diesel is regarded as 2nd Generation.

1. Policy Drivers

The U.S. Energy Independence and Security Act of 2007 (EISA) has established specific, volumetric requirements for biomass-based diesel fuel of 500 million gallons/year (mg/y) by 2009, ramping up to 1 billion gallons/year (bg/y) by 2012. Several U.S. States are also actively pursuing policies to promote greater use of biofuels. For example, California is developing a Low Carbon Fuels Standard (LCFS) and has recently passed legislation (AB-32) to address global warming concerns. Meeting California's LCFS and GHG reduction goals will require extensive use of biofuels, including biodistillates.

In Europe, EU Directive 2003-30-EC established targets for biofuels content of transportation fuels. According to this directive, biofuels must constitute 2% of transport fuels by 2005, ramping up to 5.75% in 2010. Many other countries are also beginning to develop policies to promote greater use of biodistillate fuels, with Brazil, China, and India being three of the most significant. Collectively, the policy-driven biodistillate requirements for the U.S., Europe, Brazil, China, and India total approximately 23 bg/y by 2020. However, due to limitations of feedstock supply, economics, and other factors, the actual amount of biodistillate in the marketplace is likely to be substantially less.

2. Biodiesel Volumes and Feedstocks

Current global biodistillate production stands at approximately 3 bg/y, with nearly all of this being biodiesel. Most biodiesel is blended with petroleum diesel to produce biodiesel blends, with a 20% blend, called B20, being one of the most common. About $\frac{2}{3}$ of global biodiesel production currently comes from Europe, where rapeseed oil is the dominant feedstock. In the U.S., soybean oil is the dominant feedstock. Biodiesel fuel production has increased significantly in recent years, but plant capacity has increased much more. Current plant utilization rates in Europe and the U.S. are below 25%. This underutilization is a significant problem that is not likely to be solved soon, given current economic and feedstock limitations.

There is considerable world-wide interest in developing alternative feedstocks for biodistillate fuels – particularly non-edible feedstocks. Among those receiving the greatest attention are oil bearing terrestrial plants such as jatropha and karanja. China and India have begun large-scale agricultural efforts to develop these feedstocks. Many organizations are also investigating use of microalgae as biodistillate feedstocks. After several years of inactivity, the U.S. DOE is again beginning to focus on microalgae, and is currently developing a national roadmap for algal fuels. It is likely that commercially produced biodistillates from these non-edible feedstocks will begin to appear in the marketplace within five years.

3. Biodistillate Production Technologies

Due to their high viscosities, straight vegetable oils (SVOs) are unsuitable for use in modern diesel engines. The most common method for overcoming this problem involves the chemical process called transesterification, by which triglycerides in animal fats and vegetable oils are reacted with methanol to produce fatty acid methyl esters (FAME) and glycerol. While considerable work has been conducted to determine optimum reaction conditions for producing biodiesel, improving process efficiency remains an active area of R&D. Of particular interest is development of heterogeneous catalysts to replace the homogeneous catalysts that are commonly used today, but which present challenges with respect to product quality. A significant problem with the transesterification process is co-production of glycerol. In rough terms, 1 lb. of glycerol is produced for every 10 lbs of biodiesel. Complete removal of glycerol is critical to meeting fuel specifications.

As an alternative to transesterification, triglyceride feedstocks can be catalytically hydroprocessed to produce biodistillates generally known as renewable diesel. Several processes for renewable diesel production are now in commercial use. These include stand-alone processes by Neste Oil (to produce NExBTL) and UOP (Ecofining[™]), as well as ConocoPhillips's co-processing of triglycerides with petroleum diesel feedstocks. All these processes require hydrogen and are conducted under high pressure. The products are hydrocarbons (not oxygenates), that are very similar to those found in petroleum diesel.

Renewable diesel has several advantages over biodiesel – including lack of glycerol formation, higher mass energy content, improved oxidative stability, complete absence of sulfur and nitrogen, and blending behavior that is completely compatible with petroleum diesel blendstocks. Additionally, production of these hydroprocessed biodistillates at a refinery allows for better integration with other refinery operations, and provides access to product testing laboratories. A disadvantage of renewable diesel is its relatively poor lubricity. In this regard, it is similar to paraffinic blendstocks produced by Fischer-Tropsch (FT) or other gas-to-liquids (GTL) processes. These materials generally require additive treatment, or mixing with higher lubricity blendstocks, to achieve satisfactory performance.

4. Fuel Properties and Specification

ASTM D 6751 defines biodiesel as "fuel comprised of mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats." Since these oils and fats are quite varied in their composition, biodiesel (and renewable diesel) prepared from them also have variable composition. Having considerable oxygen content, biodiesel has lower carbon and hydrogen contents compared to diesel fuel, resulting in about a 10% lower mass energy content. However, because of slightly higher fuel density, the volumetric energy content of biodiesel is only about 5-6% lower than petroleum diesel. Typically, biodiesel has somewhat higher molecular weight than petroleum diesel, which is reflected in slightly higher distillation temperatures. Consisting largely of straight chain esters, biodiesel has high cetane number – typically higher than No. 2 diesel fuel. The viscosity of biodiesel is significantly higher than petroleum diesel, often by a factor of 2.

In large part, the physical properties, performance attributes, and overall suitability of biodiesel are determined by the fuel's chemical composition. The two most important compositional factors are fatty acid chain length and the degree of unsaturation in the fatty acid chain. Unlike petroleum diesel, biodiesel contains virtually no branched chain paraffinic structures, naphthenes, or aromatics. All common triglycerides are dominated by even-numbered carbon chains, with C_{16} and C_{18} being the largest components.

Renewable diesel consists mainly of paraffinic hydrocarbons, having 15 or 17 carbon atoms, as one carbon from the triglyceride feedstock is typically lost during hydroprocessing. Renewable diesel has excellent combustion properties, as indicated by its high cetane number. On a mass basis, the energy

content of renewable diesel is very high, slightly exceeding that of typical No. 2 ULSD. However, due to its relatively low density, the volumetric energy content of renewable diesel is significantly lower than that of No. 2 diesel, and similar to biodiesel. A summary of typical properties of biodiesel and renewable diesel is provided in Table ES-1, along with properties of No. 2 ULSD.

Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
Т _{90,} °С	300-330	330-360	290-300
Viscosity, mm ² /sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Table ES-1. Typical Properties of Petroleum Diesel and Biodistillate Fuels

Several standard-setting organizations have developed sets of standard specifications to define acceptable quality of biodistillate fuels. The two most widely accepted organizations are ASTM (in the U.S.) and the European Committee for Standardization (CEN). ASTM has established standard specifications for biodiesel fuel blendstocks (B100) for middle distillate fuels, called ASTM D 6751. The CEN's standard specifications for B100 are called EN 14214. At the present time, only the U.S. has established a separate standard specifications for conventional No. 2 diesel fuel (ASTM D 975) were modified to permit low level blends of biodiesel – B5 and below. Also, the European standard specifications for conventional No. 2 diesel fuel (EN 590) are being modified to allow for low lead blends of biodiesel. No special standards have been established for renewable diesel, but finished diesel fuel that contains renewable diesel must comply with the appropriate standards for No. 2 diesel fuel (ASTM D 975 in the U.S.; EN 590 in Europe).

To help promote satisfactory biodiesel product quality in the U.S., the National Biodiesel Board has established a National Biodiesel Accreditation Commission to oversee the BQ-9000 Quality Management System. This Commission has recently issued two sets of requirements: one for B100 producers; the other for B100 marketers. These requirements define acceptable documentation practices, laboratory operations, sampling and testing methods, fuel blending and distribution procedures, and storage conditions.

5. In-Use Handling and Performance of Biodiesel Fuels

Because some properties of biodiesel differ from those of conventional diesel fuel, extra precautions must be taken to ensure proper handling practices are followed, so that products having acceptable quality are delivered to the end user. Under special circumstances, B100 may be utilized, though blending levels of B20 and below are most common in the U.S. today. B20 is the highest blend level specified by ASTM, and is also the highest level recommended by many engine and vehicle original equipment manufacturers (OEMs) for selected models. (Most engine models are not considered B20 compatible.) The quality of biodiesel in the marketplace has been a concern. Steps to address this concern have been taken in recent years by adoption (or modification) of ASTM Standards D 6751 (for B100) and D 7467 (for B6-B20), and by development of the BQ-9000 Quality Management System. Fuel quality surveys indicate that problems with blending control and off-spec products were common in the past. However, with more stringent fuel specifications and increasing producer experience, the overall quality of biodiesel in the marketplace has improved. It should be pointed out, however, that ASTM has no mechanism for enforcing their fuel requirements.

In general, biodiesel has somewhat poorer oxidative stability and low-temperature operability than petroleum diesel, though the extent of the differences varies substantially based upon the unique chemical composition of the biodiesel in question. Low temperature operability can be improved by proper selection of triglyceride feedstocks, greater dilution with petroleum diesel, use of cold flow improver additives, and use of ethanol rather than methanol in the transesterification process.

Water solubility and water contamination are other issues of concern. The generally higher water levels in biodiesel can exacerbate problems with corrosion, wear, suspension of solids, and microbial growth. When dealing with biodiesel, extra "housekeeping" precautions may be necessary to remove excess water and sediment. In particular, this is required when first introducing biodiesel into tanks (both stationary and vehicular) previously used for conventional diesel, as accumulated water and sediment may become dispersed and plug filters under these conditions.

Due to its different physical and chemical properties, introducing biodiesel into systems designed for petroleum diesel raises questions about materials compatibility and other potentially adverse impacts on fuel or engine systems. These concerns are greatest when using B100. Limiting biodiesel blends to B20 and below, and ensuring that only on-spec fuel is used, greatly reduces most concerns regarding in-use handling and performance.

6. Exhaust Emissions Impacts

Diesel vehicles are a significant source of both NO_x and PM emissions and, to a lesser extent, CO, HC, and other toxic species. Since NO_x is a precursor to ozone (O_3) formation, it is also a key variable in the development of control strategies to reduce this secondary pollutant. The impacts of biodiesel upon NOx emissions have been a topic of controversy for many years. In this study, emissions results published in 94 literature references were examined. These reports include HD, LD, and single-cylinder test engines (TE) utilizing both engine and chassis dynamometers, operating under a wide variety of transient and steady-state conditions. Many different biodiesel blend levels have been investigated, using fuels produced from numerous different feedstocks. Relatively few reports of emissions from renewable diesel appear in the literature.

Emissions data were analyzed by comparing results from a biodistillate fuel and a conventional diesel fuel determined in the same experimental study. Logarithmic regressions were used to express the percent change in emissions of a given pollutant as a function of biodistillate blend level. The results of these analyses for HD engine cases are shown as solid lines in Figure ES-1, where they are compared with previous EPA results (dashed lines).

Use of biodistillates, even at a B20 level, substantially decreases emissions of CO, HC, and PM – generally by 10-20%. Although results vary considerably from one study to the next, similar benefits are typically seen in both LD and HD engines, regardless of engine technology or test conditions. While data are much more limited for renewable diesel cases, it appears that these hydroprocessed fuels also provide similar emissions reduction benefits for CO, HC, and PM.

NOx emissions impacts are much smaller, and more difficult to discern. Though highly variable, most studies indicate a slight NOx increase when using B100 fuel. For HD engines, our best estimates are that NOx emissions increase 2-3% with B100, but are unchanged from conventional diesel fuel for B20 blends. Thus, our review indicates overall lower NOx effects of biodistillates than defined by EPA several years ago (see Fig. ES-1). Accurate quantification of these fuel effects would require more sophisticated statistical analyses.



Figure ES-1. Emissions effects of biodistillates from HD dynamometer tests

7. Life-Cycle Analysis and Land Use Impacts

In comparing energy and environmental impacts of different fuels, it is increasingly recognized that the entire life-cycle of the fuel must be considered. In fact, life-cycle models have become a common aid for policy regarding the use of alternative fuels. Life-cycle assessments (LCA) provide a tool to evaluate the energy and environmental impacts (especially greenhouse gas emissions) that result from all stages of a product's life, from manufacturing through disposal. Full fuel LCAs are commonly broken into two parts: (1) well-to-tank (WTT) and (2) tank-to-wheels (TTW). The combination of the two parts represents the complete well-to wheels (WTW), or "cradle-to-grave," life-cycle for a transportation fuel.

The WTT pathway for a biodistillate fuel commonly includes growth of crops, which may involve landuse change (LUC) and farming inputs like fertilizers, harvesting, processing or crushing to extract the oil, production (via transesterification or some other method), and distribution to the fueling station. The TTW analysis includes combustion of the fuel in a vehicle, and depends on the type of vehicle, its efficiencies and driving mode. Common LCA practice for biofuels is to ignore non-fossil CO₂ emitted during combustion of the fuel, since this carbon was recently taken up by the plant during its growth through photosynthesis. With this assumption, the WTT results for GHG emissions of biofuels are similar to the complete WTW results. Although established databases and modeling tools exist, differences in LCA modeling approaches are still common. Different methodologies arise from variations in defining fuel pathways, scenario boundaries, input assumptions, and dealing with co-products. One important area of difference involves land use changes (LUC) – both direct and indirect. Direct LUC impacts are associated with the cultivation of feedstocks used to produce a biofuel in the region where it is used. Indirect LUC effects are those that could potentially arise when a crop is produced in one region of the world in response to fuel demand changes in another region.

Most LCA models include some type of direct LUC assessment to address changes in GHG emissions resulting from modifications to agricultural practices. Methods of including direct LUC are somewhat controversial, specifically with respect to N_2O , a potent GHG produced in the soil by biological processes. Variations in assumptions about N_2O can swing the final GWP results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

Indirect LUC has been a topic of recent publicity and concern. As crops are diverted to fuels in one geographic location, increased crop production may be required elsewhere to compensate. This increased production could occur through displacement of existing crops, expansion of croplands, or intensification of existing production. At present, most LCA models do not include the effects of indirect LUC. However, policy is trending towards including indirect LUC into already required LCA models. To do this, some type of economic model is required to estimate the economic supply and demand of developing new crop lands.

Another major source of variation among LCA results is the method by which co-products (such as glycerol, feed meal, propane, etc.) are treated. Common practice in LCA modeling is to allocate some of the energy and emissions produced during the fuel life-cycle to these co-products. However, as with LUC, differences in co-product allocation assumptions can swing the final LCA results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

The life-cycle energy use required to produce a unit of fuel is usually assessed in an LCA. The overall energy benefit, or energy return (ER), of the entire process is determined by dividing the energy out of the process (the heating value of the fuel) by the total life-cycle energy inputs. A net energy benefit results when the ER is greater than one; an ER less than one indicates more energy is required to produce the fuel than is contained in the final product. Common practice in biofuel LCA is to include only fossil energy inputs in the calculation of ER. This typically results in an ER value greater than one for biodistillates, but slightly less than one for conventional diesel fuel. Of the 19 published LCA reports we reviewed, most gave ER results between 2 and 4, for both biodiesel and renewable diesel.

LCA results for GHG emissions are usually expressed in terms of relative global warming potential (GWP). In almost every published LCA study, biodistillate scenarios resulted in lower GWP compared to conventional diesel. In the 24 studies we investigated, the GWP benefits of the biodistillate fuels ranged from 10% to 90%, with an overall average value of about 60%. However, there are a few exceptions, mainly due to assumptions of high N_2O emissions, where biodiesel scenarios showed overall GWP disbenefits compared to conventional diesel. These GWP results are shown in Figure ES-2.

In addition to GWP and energy requirements, other ecological or resource impacts are often assessed using LCA methodologies. Some of the most important impact categories pertain to water resources, eutrophication, acidification, and photochemical ozone creation potential. However, compared to GWP and energy impacts, assessments of these other life-cycle impacts are still in their infancy.



Figure ES-2. Relative GWP for 24 Biodiesel LCA Studies (Study No's identified in Appendix VI)

Technical Summary

Production and use of biofuels are increasing dramatically, both in the U.S. and globally. While most interest has been focused on ethanol and its use in light-duty gasoline vehicles (LDGV), considerable growth in biofuels for diesel applications is also occurring. Policy drivers for this growth include the following:

- National energy security
- Diversity of energy sources
- Concerns over greenhouse gases (GHGs) and global climate change
- Desire for sustainable energy sources
- Rural economic development
- Improved balance of trade

The main purpose of this study is to assess the state-of-knowledge regarding plant- and animal- derived biofuels as blending materials for ultra-low sulfur diesel (ULSD) fuel in transportation applications. Topics of interest include policy drivers, biofuels feedstocks, fuel production technologies, fuel properties and specifications, in-use handling and performance, exhaust emissions effects, and life-cycle impacts. Data gaps were identified and areas for further work have been recommended.

The comprehensive term, biodistillate, is used to include all plant- and animal- derived middle distillate fuels intended for diesel engines, regardless of the production technology used to manufacture the fuel. This includes both biodiesel (produced via transesterification of animal fats and vegetable oils) and renewable diesel (produced via catalytic hydrotreatment of the same feedstocks). Additionally, distillate fuels produced from lignocellulosic feedstocks are considered biodistillates, though such fuels are not in use today. Straight vegetable oils (SVOs) are not classified as biodistillate, as their boiling point distributions are considerably higher than common distillate fuels.

The term "1st Generation" refers to biofuels produced from commonly available, edible feedstocks using well-established conversion technologies. Most biofuels in use today are classified as 1st Generation. This includes ethanol produced via fermentation of sugars (from corn, sugar cane, sorghum, etc.) and biodiesel produced via transesterification of triglycerides (from vegetable oils and animal fats) to produce fatty acid methyl esters (FAME).

The term "2nd Generation" can refer to biofuels produced from either advanced, non-food feedstocks, or produced via advanced processing technology (or both). Examples of advanced feedstocks include lignocellulose and non-edible triglycerides, such as jatropha and algae. Examples of advanced processing technology include catalytic hydroprocessing of triglycerides and thermal conversion (gasification and pyrolysis) of lignocellulose.

In this report, the term "1st Generation" is used to refer to biodiesel (FAME) produced via transesterification of edible triglycerides (including waste cooking fats and oils). The term 2nd Generation is used to refer to Renewable Diesel, Green Diesel, and biodiesel produced via transesterification of non-edible triglycerides. This report summarizes the state of knowledge for both 1st Generation and 2nd Generation biodistillates.

1. Policy Drivers for Biodistillate Fuels

At present, the dominant U.S. policy driver for biodistillate fuels is the Energy Independence and Security Act of 2007 (EISA). (Prior to EISA, the main policy driver for biodistillate fuels was the \$1/gallon blenders' tax credit.) Through EISA, for the first time, Congress has established specific, volumetric

requirements for biodiesel of 500 million gallons/year (mg/y) by 2009, ramping up to 1 billion gallons/year (bg/y) by 2012. With current on-road diesel fuel usage in the U.S. at approximately 40 bg/y; the maximum EISA biodiesel requirement represents about 2.5% of this total. EISA also establishes a total renewable fuel standard (RFS) requirement of 36 bg/y, to be met by 2022, with 21 bg/y of this coming from "advanced biofuels," meaning fuels derived from renewable biomass (excluding ethanol derived from corn) that achieve at least a 50% reduction in greenhouse gas (GHG) emissions, on a lifecycle basis.

Several U.S. States are actively pursuing policies to promote greater use of biofuels. California is developing a Low Carbon Fuels Standard (LCFS) and has recently passed legislation (AB-32) to address global warming concerns. AB-32 goals require statewide reduction of GHGs to achieve the 2000 level by 2010, the 1990 level by 2020, and 80% below the 1990 level by 2050. These reductions will be based upon "life-cycle values" by a mechanism that is still being defined. Meeting California's LCFS and GHG reduction goals will require extensive use of biofuels, including biodistillates.

In Europe, EU Directive 2003-30-EC established targets for biofuels content of transportation fuels. According to this directive, biofuels must constitute 2% of transport fuels by 2005, and grow by 0.75% absolute per year until reaching 5.75% in 2010. These requirements apply to all transportation fuels, not just diesel fuel, though 75-80% of the requirement is being met by use of biodiesel. The EU has also defined a "benchmark" of achieving 20% biofuels content by 2020, though there is no legally binding requirement for this.

Many other countries are also beginning to develop policies to promote greater use of biodistillate fuels. Three of the most important are: (1) Brazil, which enacted a National Biodiesel Production Program in 2004, (2) China, which established a Renewable Energy Law in 2005, and (3) India, which developed a National Mission on Biodiesel in 2003.

All these national and regional policies include volumetric targets for biodistillate production that increase with time. Some targets are legally binding, while others are not. Combining the targets from all 5 regions (U.S.,

Europe, Brazil, China, and India) gives a projected biodistillate production volume of 23 bg/y by 2020 (see Figure TS-1). However, many of these targets are extremely optimistic, and are unlikely to be met in the timeframe specified. Given the constraints of feedstock availability, competition for other uses of some feedstocks, and global economic realities, we believe the total biodistillate production volumes by 2020 may be only 1/3 as large as shown in Figure TS-1.



Figure TS-1. Policy-Driven Volumetric Biodiesel Requirements

2. Biodiesel Volumes and Feedstocks

As shown below in Fig. TS-2, global biodiesel production has increased substantially in recent years. Europe has been – and continues to be – the dominant region for biodiesel. However, feedstock supply is expected to limit Europe's biodiesel production to well below the 5.75% goal by 2010.

Growth of biodiesel in the U.S. is also limited by feedstock supply and cost. Approximately 80% of total biodiesel cost is attributed to feedstock. While biodiesel production has grown significantly in both Europe and the U.S., plant capacity growth has been even more dramatic. Consequently, capacity utilization is declining. Utilization in the U.S. was 42% of capacity in 2006, but was estimated to be below 25% in 2008.



Figure TS-2. Global Growth in Biodiesel Production

While numerous alternative feedstocks are now beginning to receive attention, the only biodistillate feedstocks used commercially to-date have been triglycerides from animal fats and seed oils. As shown in Fig. TS-3, the dominant biodiesel feedstock in the U.S. (and Brazil) is soybean oil, although a number of other materials are also used. This is in contrast to the European countries, where rapeseed oil dominates. Waste cooking oil, canola oil, animal fats, and other triglycerides are finding increased usage in the U.S. as soybean oil supplies are becoming more limited and costly.

In the U.S., approximately 70 million acres of U.S. farmland are used for soybean cultivation. The fraction of the soybean crop used for biodiesel production is small, but increasing. Accurate determinations are difficult to make, since only a small portion of the soybean oil is used for fuel production, while the majority is used for animal feed and other purposes. However, it is estimated that the fraction of the total soybean crop devoted to biodiesel was 6% in 2005-2006, 8% in 2006-2007, and could reach 20% in 2008. A recent DOE study has concluded that a 3 bg/y U.S. biodiesel industry would require 30 million acres of cropland to be used for seed oil production. Achieving this level of biofuels will also require substantial increases in seed oil yield per acre. Numerous R&D efforts are underway to improve agricultural productivity in general, and to genetically modify crops for enhanced yields and improved fuel properties.

At the present time, China has approximately 4 million hectares (10 million acres) of land area for growing oil-bearing trees, with an increasing fraction being devoted to jatropha. The first sizeable harvest of jatropha trees (also called "diesel trees" in China) is expected in 2008. By 2010, China anticipates having 13 million hectares (32 million acres) planted in jatropha – a size approximately equal to the landmass of England. Once fully productive, this could provide 2-4 bg/y of biodiesel.



Figure TS-3. Biodiesel Feedstocks by Country – 2007

Current feedstocks for biodiesel production in India are quite varied, including waste vegetable oil, animal fats, rubberseed oil, rice bran, karanja, pongamia, and especially jatropha. Due to government policies and high edible oil prices, it is not feasible to produce biodiesel from vegetable oils in India today. While still in its infancy, India intends to greatly expand its use of jatropha. To meet the 5% biodiesel goal by 2010 will require approximately 2.5 million hectares (6.3 million acres) of jatropha and karanja. Meeting the 20% goal by 2020 would require about 20 million hectares (50 million acres). Significant advantages of jatropha (and some other native plants) include its ability to grow on marginal land with modest requirements for water and fertilizer. In India (and elsewhere) developing a jatropha industry is also seen as a powerful driver for rural economic development.

Many varieties of microalgae are known to produce large quantities of lipids, consisting mainly of triglyceride oils, which are potential feedstocks for biodistillate fuels. Of all photosynthetic organisms, microalgae are the most productive users of CO₂, and can fix larger amounts of CO₂ per land area than other plants. Various investigations have been conducted to determine suitable algal strains for maximum growth and oil production under specific conditions. The most comprehensive investigation of algae as a potential fuel feedstock was undertaken by the National Renewable Energy Laboratory, who maintained an active Aquatic Species Program (ASP) from 1978 to 1996. The ASP final closeout report was issued in 1998, and remains an excellent source of information about growth conditions and productivities of various algal strains.

Due to numerous technical and economic factors, the ASP was discontinued. Now, however, DOE and NREL have renewed interest in promoting algae as a commercial energy source. In fact, DOE recently sponsored an "Algal Fuels Roadmapping" meeting, and plans to issue a roadmap document in mid-2009. Reasons cited for this renewed interest include the following:

- High costs of petroleum and other energy sources
- Increased emphasis on energy security
- Concern about CO₂ and climate change
- Advances in biotechnology and photobioreactor designs
- Petroleum refiners' interest in processing lipids

Major barriers to commercial scale implementation of algal systems include numerous technical challenges (maintaining healthy algal growth, avoiding invasive native algae, temperature control, effective light dispersion, reliable harvesting methods, effective oil extraction, and others) as well as economics.

3. Biodistillate Production Technologies

Although straight vegetable oils (SVOs) have been used as fuels in compression-ignition engines, they are generally regarded as unsuitable for use in modern diesel engines. The most unacceptable attribute of SVO is high viscosity, that causes poor fuel atomization and combustion, injector coking, deposit formation, and other problems. These problems can be reduced, but not eliminated, by diluting the SVO with conventional diesel fuel.

The most common method for overcoming the problems of SVO involves the chemical process called transesterification, by which triglycerides are reacted with alcohols to produce fatty acid alkyl esters and glycerol. These fatty acid esters [usually fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE)] are commonly known as biodiesel.

Considerable work has been conducted to determine optimum reaction conditions for producing biodiesel. To some degree, different conditions are required for each triglyceride feedstock. For a given feedstock,

numerous factors have been found to have significant impacts on process efficiency and purity of the final product. The most important parameters influencing the production and quality of biodiesel are the following:

- Ratio of alcohol to triglyceride
- Type of alcohol
- Purity of triglyceride feedstock
- Amount and type of catalyst
- Reaction time and temperature

Improving the efficiency of biodiesel production and purification remains an active area of R&D. Of particular interest is development of heterogeneous catalysts to replace the homogeneous hydroxide (or alkoxide) catalysts that are commonly used today, but which present challenges with respect to product quality. Other improvements being investigated include transesterification under supercritical alcohol conditions, use of co-solvents, and use of ultrasonic or microwave radiation to accelerate the rate of reaction.

A significant problem with the transesterification process is co-production of glycerol. In rough terms, 1 lb. of glycerol is produced for every 10 lbs of biodiesel. Complete removal of glycerol from biodiesel is critical to meeting fuel specifications. While high purity glycerol has many commercial outlets, the increasing production of biodiesel has led to a surplus of relatively low quality glycerol, which requires further refining to increase its value.

As an alternative to transesterification, triglyceride feedstocks can be hydroprocessed to produce biodistillates, generally known as renewable diesel. One of the first commercial processes was reported in 2005, by Neste Oil Corporation. The product, called NExBTL, is a paraffinic hydrocarbon material suitable for blending into conventional diesel fuel. UOP, in conjunction with Eni, has developed a similar process called Ecofining[™]. More recently, ConocoPhillips has developed a related process in which triglycerides are co-fed with petroleum feedstocks into a conventional diesel hydrotreater unit used for desulfurization.

In all of these hydroprocessing cases several reactions occur, including hydrogenation of olefinic groups within triglycerides, decarbonylation (loss of CO), decarboxylation (loss of CO₂) and hydrodeoxygenation (loss of H₂O). Most of the glycerol component within the original triglyceride is converted to light hydrocarbons (especially propane), while most of the carboxyl carbons are converted to CO or CO₂. Since triglyceride compositions are dominated by even-numbered fatty acid components, removal of the carboxyl group results in biodistillates consisting mainly of odd-numbered paraffins.

These hydroprocessed biodistillates have several advantages over biodiesel – including lack of glycerol formation, higher mass energy content, improved oxidative stability, complete absence of sulfur and nitrogen, and blending behavior that is completely compatible with petroleum diesel blendstocks. Additionally, production of these hydroprocessed biodistillates at a refinery allows for better integration with other refinery operations, and provides access to product testing laboratories.

A disadvantage of hydroprocessed biodistillates is their relatively poor lubricity characteristics. In this regard, they are similar to paraffinic blendstocks produced by Fischer-Tropsch (FT) or other gas-to-liquids (GTL) processes. These materials generally require additive treatment, or mixing with higher lubricity blendstocks, to achieve satisfactory performance. Other disadvantages of renewable diesel production include the high capital cost of hydroprocessing equipment, and the need to manufacture and deliver hydrogen.

The literature contains several reports of pyrolysis (or thermal cracking) of triglycerides to produce biodistillates. This option may be advantageous when dealing with certain low-quality triglyceride feedstocks, which are difficult to treat via transesterification. Pyrolysis of lignocellulosic material to produce liquid transportation fuels is an extremely active area of research. However, significant problems with these pyrolysis approaches remain to be overcome – particularly effective means of avoiding char formation, and stabilizing the pyrolysis oils that are produced. Pyrolysis oils produced from lignocellulosic feedstocks are highly oxygenated and chemically reactive, requiring considerable upgrading to be used as transportation fuels.

4. Fuel Properties and Specification

ASTM D 6751 defines biodiesel as "fuel comprised of mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats." A more common definition of biodiesel is fatty acid methyl esters (FAME) produced from fats and oils. Since these oils and fats are quite varied in their composition, biodiesel (and renewable diesel) prepared from them also have variable composition. Having considerable oxygen content, biodiesel has lower carbon and hydrogen contents compared to diesel fuel, resulting in about a 10% lower mass energy content. However, because of slightly higher fuel density, the volumetric energy content of biodiesel is only about 5-6% lower than petroleum diesel. Typically, biodiesel has somewhat higher molecular weight than petroleum diesel, which is reflected in slightly higher distillation temperatures (as measured by T₉₀). Being largely straight chain paraffinic esters, most biodiesel fuels have excellent cetane numbers – typically higher than No. 2 diesel fuel. The viscosity of biodiesel fuels is typically higher than petroleum diesel, often by a factor of 2.

Renewable diesel consists mainly of paraffinic hydrocarbons having 15 or 17 carbon atoms. While some renewable diesel fuels contain primarily straight-chain, normal paraffins, others contain appreciable amounts of branched paraffins. As a consequence of their paraffinic structure, biodiesel fuels have very high cetane numbers and excellent combustion properties. On a mass basis, the energy content of renewable diesel is very high, slightly exceeding that of typical No. 2 ULSD. However, due to its relatively low density, the volumetric energy content of renewable diesel is significantly below that of No. 2 diesel, but is similar to biodiesel. A summary of typical properties of biodiesel and renewable diesel is provided in Table TS-1, along with typical properties of No. 2 ULSD. Properties of individual fuels can vary somewhat from those shown here.

Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
T _{90,} °C	300-330	330-360	290-300
Viscosity, mm ² /sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Table TS-1. Typical Properties of Petroleum Diesel and Biodistillate Fuels

In large part, the physical properties, performance attributes, and overall suitability of biodiesel are determined by the fuel's chemical composition. The two most important compositional factors are fatty acid chain length and the degree of unsaturation in the fatty acid chain. Unlike petroleum diesel, biodiesel

contains virtually no branched chain paraffinic structures, naphthenes, or aromatics. All common triglycerides are dominated by even-numbered carbon chains, with C_{16} and C_{18} being the largest components. Some oils are dominated by saturated carbon chains, while others are dominated by unsaturated chains. Examples of this extreme diversity are provided by coconut oil (which is about 90% saturated) and safflower seed oil (which is about 90% unsaturated). Compositional profiles of the most common biodiesel feedstocks, (soybean oil in the U.S.; rapeseed oil in Europe) are depicted below in Fig. TS-4. This figure shows significant differences between the two feedstocks, with soybean being dominated by linoleic acid (18:2) and rapeseed being dominated by oleic acid (18:1).



Figure TS-4. Compositional Profiles of Soybean Oil and Rapeseed Oil

Several standard-setting organizations have developed sets of standard specifications to define acceptable quality of biodistillate fuels. The two most widely accepted organizations are ASTM (in the U.S.) and the European Committee for Standardization (CEN). ASTM has established standard specifications for biodiesel fuel blendstocks (B100) for middle distillate fuels, called ASTM D 6751. The CEN's standard specifications for B100 are called EN 14214. At the present time, only the U.S. has established a separate standard for biodiesel blends – ASTM D 7467 is applicable to blends of B6 to B20. Recently, the U.S. standard specifications for conventional No. 2 diesel fuel, ASTM D 975, were modified to permit low level blends of biodiesel – B5 and below. Also, the European standard specifications for conventional No. 2 diesel fuel (EN 590) are being modified to allow for low level blends of biodiesel. In most other locations, blends of B20 and below are acceptable if both the biodiesel component and petroleum diesel component meet their respective standards. No special standards have been established for renewable diesel, but finished diesel fuel that contains renewable diesel must comply with the appropriate standards for No. 2 diesel fuel (ASTM D 975 in the U.S.; EN 590 in Europe).

A major reason for many of the specifications in the B100 standards is to ensure high purity FAME, free of contaminants and unreacted starting materials that could otherwise lead to poor performance with respect to storage stability, injection quality, corrosion, deposit formation, emissions, or other problems. One particular concern is durability of particulate traps that are critical components of a vehicle's emissions control system. To ensure long life of these traps, it is important that total ash levels of biodiesel -- as well as levels of individual element such as Ca, Mg, Na, K, and P -- be kept very low.

To help promote satisfactory biodiesel product quality in the U.S., the National Biodiesel Board has established a National Biodiesel Accreditation Commission to oversee the BQ-9000 Quality Management System. This Commission has recently issued two sets of requirements: one for B100 producers; the other for B100 marketers. The BQ-9000 Producers Requirements define acceptable documentation practices, management responsibilities, laboratory operations, sampling and testing methods, fuel blending and loading requirements, and other aspects of a Quality Management System. The BQ-9000 Marketers Requirements include many of the same elements with respect to documentation, management responsibilities, and laboratory procedures, but also address issues of fuel storage, blending, and distribution.

A critical aspect of fuel quality is establishment and operation of a competent fuel testing laboratory. Small "Mom and Pop" producers of biodiesel generally do not have the necessary equipment or expertise to conduct the full range of tests specified in ASTM D 6751 for B100. Even in such cases, however, a subset of the most critical QC tests should be conducted on-site for every batch, with other tests being conducted periodically, using outside laboratories. Table TS-2 provides the authors' recommendations for laboratory QC tests that should be conducted to ensure high quality biodiesel. The tests recommended for every batch of B100 are the same ones identified by previous reviewers, with addition of the Rancimat oxidative stability test and the cold soak filterability test. This list is similar, but not identical, to the BQ-9000 Producer Requirements.

QC Tests to be Conducte	d on Every Batch	QC Tests to be Conducted Periodically		
Property	Test Method	Property	Test Method	
Water and Sediment	D 2709	Cetane Number	D 613	
Viscosity	D 445	Methanol	EN 14110	
Flash Point	D 93	Metals (Na, K, Ca, Mg)	EN 14538	
Cloud Point	D 2500	Total Sulfur	D 5453	
Sulfated Ash	D 874	Phosphorous	D 4951	
Acid Number	D 664	Carbon Residue	D 4530	
Free and Total Glycerin	D 6584	T ₉₀	D 1160	
Copper Strip Corrosion	D 130	Ester Content*	EN 14103	
Oxidative Stability	EN 14112	Iodine Number*	EN 14111	
Cold Soak Filterability	D 6751 Annex A1			

Table TS-2. QC Laboratory Testing Recommendations for B100

* Required for European fuels only

5. In-Use Handling and Performance of Biodiesel Fuels

Because some properties of biodiesel differ from those of conventional diesel fuel, extra precautions must be taken to ensure proper handling practices are followed, so that products having acceptable quality are delivered to the end user. Under special circumstances, B100 may be utilized. However, for use as a transportation fuel, only blends of biodiesel with conventional diesel are generally recommended. The literature is replete with studies where various blend ratios of biodiesel have been used. For research and development purposes, investigations of wide blending ranges are valuable, since this provides a better understanding of fuel effects on injection behavior, engine performance, emissions, materials compatibility, and other factors. For commercial use, however, a much narrower range of biodiesel blend ratios is desirable. In the U.S. today, biodiesel blend levels of B20 and below are most common. B2 and B11 are required (or encouraged) by regulation in some locations; B20 is the highest blend level specified by ASTM. B20 is also the highest level recommended by many engine and vehicle original equipment manufacturers (OEMs) for selected models. (Most engine models are not considered B20 compatible.)

One of the biggest concerns of the biodiesel industry is the quality of finished fuels being used in the marketplace. The use of poor quality fuels can lead (and has led) to field problems and customer complaints, which reduce public confidence and jeopardize the future of the industry. Steps to address these concerns have been taken in recent years by adoption (or modification) of ASTM Standards D 6751 (for B100) and D 7467 (for B6-B20), and by development of the BQ-9000 Quality Management System. Fuel quality surveys have indicated that problems with blending control and off-spec products were common in the past. However, it appears that with more stringent fuel specifications and increasing producer experience, the overall quality of biodiesel in the marketplace is improving.

Ensuring satisfactory oxidative stability of biodiesel in the marketplace is a major product quality concern. Due to the complex degradation pathways involved, no single test method is fully able to assess fuel stability in all circumstances. One of the most widely utilized test methods is the Rancimat oxidative stability test (EN 14112), which is based upon detection of volatile, secondary oxidation products that result from reaction of biodiesel with oxygen at elevated temperature. The Rancimat test was only recently (2007) incorporated in the ASTM standard specifications for B100. This test was originally developed as an indicator of vegetable oil storage stability, but is also regarded as a suitable means to assess storage stability of biodiesel and its blends. (Another oxidation stability test, prEN 15751, has been provisionally accepted.)

For many users, low temperature operability is the greatest biodiesel concern, particularly during cold seasons of the year. Just as with conventional diesel fuel, precautions must be taken to ensure satisfactory low temperature operability of biodiesel and its blends. These concerns are often greater with biodiesel, due to its higher cloud point and pour point compared to petroleum diesel. Poor low temperature operability may be exhibited in several ways, but principally by filter plugging due to wax formation, and engine starving due to reduced fuel flow.

As with fuel stability, there is no single best test to assess low temperature operability. U.S. fuel standards do not include explicit specifications for low temperature operability – either for conventional diesel or biodiesel (or blends of the two). However, the fuel seller is generally required to give an indication of low temperature operability by reporting the cloud point (CP) of the fuel. Also, a cold-soak filterability standard test method for B100 is under development by ASTM. Beginning in 2008, ASTM D 6751 required test method "Annex A1" to assess cold soak filterability of B100 intended for blending with ULSD.

Poor low temperature operability is usually caused by long-chain saturated fatty acid esters present in biodiesel. In general, the longer the carbon chain, the higher the melting point, and poorer the low temperature operability. The presence of carbon–carbon double bonds significantly lowers the melting point of a molecule (hydrocarbon or fatty acid alkyl ester). Therefore, to a certain degree, a trade-off exists between fuel stability and low temperature operability. With increasing extent of unsaturation, stability decreases but low temperature operability improves.

In large part, the fatty acid composition of the fats and oil precursors to biodiesel dictate the low temperature operability of the final fuels. Feedstocks with highly saturated fatty acid structures (such as palm oil and tallow) produce biodiesels with poor operability; whereas feedstocks with highly unsaturated fatty acid structures (such as rapeseed and safflower oil) have better operability. Proper choice of feedstocks is critical to providing a finished biodiesel fuel having acceptable low temperature operability. Other approaches that are helpful in particular circumstances include the following:

- Blending with petroleum diesel
- Use of commercial petroleum diesel additives
- Use of new cold flow improver (CFI) additives for biodiesel
- Use of higher alcohols (including ethanol) for transesterification
- Crystallization fractionation (wax removal)

Although the viscosity of a biodiesel is much lower than that of its triglyceride feedstock, it is typically higher than that of petroleum diesel – often by a factor of two. Viscosity can have significant effects on the injection quality of distillate fuels. In general, higher viscosity leads to poorer fuel injection and atomization. Biodiesel users have very few options to improve the viscosity of the fuel. The only practical approaches involve heating the fuel or diluting it with petroleum diesel (or renewable diesel). Low

concentration blends of biodiesel (B20 and below) generally have acceptable viscosity, and do not cause significant field problems.

In the U.S., lubricity specifications apply to both conventional diesel and B6-B20 blends of biodiesel. B100 does not have a lubricity specification. In fact, the natural lubricity of neat B100 is so high that a 1-2% blend of it with ULSD is generally sufficient to meet the lubricity specification of D 975. In part, biodiesel's good lubricity can be attributed to the ester group within the FAME molecules, but a higher degree of lubricity is due to trace impurities in the biodiesel. In particular, free fatty acids and monoglycerides are highly effective lubricants. It has been noted that purification of biodiesel by means of distillation reduces its lubricity because these high-lubricity impurities are removed. The effect of unsaturation upon lubricity is unclear, with some researchers reporting positive effects of carbon-carbon double bonds while others report no effect.

Due to its different physical and chemical properties, introducing biodiesel into systems designed for petroleum diesel raises questions about materials compatibility and other potentially adverse impacts on fuel or engine systems. Materials compatibility pertains to the impacts of biodiesel upon seals, gaskets, hoses, metal surfaces, and other materials that the fuels contact. It is well known from laboratory studies and in-use experience that changes in fuel composition can affect the integrity of elastomeric materials. In particular, changes in swelling, shrinkage, embrittlement, and tensile strength are of concern, as extreme changes in these properties can lead to seal failures, leaks, and subsequent problems. Materials compatibility issues are of greatest concern with use of B100. Limiting biodiesel blends to B20 and below, and ensuring that only on-spec fuel is used, greatly reduces these concerns.

Water solubility and water contamination are other issues of concern. At room temperature, water is very slightly soluble in conventional diesel fuel (<100 ppm), but has significant solubility in B100 (up to 1200 ppm). Water solubility in B20 is intermediate between these two extremes. The generally higher water levels in biodiesel can exacerbate problems with corrosion, wear, suspension of solids, and microbial growth. When dealing with biodiesel, extra "housekeeping" precautions may be necessary to remove excess water and sediment. In particular, this is required when first introducing biodiesel into tanks previously used for conventional diesel, as accumulated water and sediment may become dispersed and plug filters under these conditions.

6. Exhaust Emissions Impacts

Diesel vehicles are a significant source of both NO_x and PM emissions and, to a lesser extent, CO, HC, and other toxic species. Since NO_x is a precursor to ozone (O₃) formation, it is also a key variable in the development of control strategies to reduce this secondary pollutant. The impacts of biodiesel upon exhaust emissions have been a topic of interest for many researchers. A thorough review of B20 emissions impacts in HD engines was conducted by EPA and documented in a 2002 report. In 2006, another review of this topic was conducted by NREL.

In this current study, emissions results published in 94 literature references were examined. These reports include HD, LD, and single-cylinder test engines (TE) utilizing both engine and chassis dynamometers, operating under a wide variety of transient and steady-state conditions. Many different biodiesel blend levels have been investigated, using fuels produced from numerous different feedstocks.

Considering this wide variety of engine configurations, fuels, and testing conditions, it is very difficult to compare directly the measured emissions levels from different studies. To overcome this problem, we expressed all results as the percent change in emissions levels between a test biodistillate fuel and a reference fuel used in the same study. If a particular publication did not include a reference diesel fuel for comparison, the biodistillate results were not used in our analysis. Using this approach, the impacts of

specific biodistillate blends on emissions could be discerned more clearly. Graphical displays were developed to illustrate the variation in results across different studies, and to show emissions trends as a function of biodistillate blend level. Examples of these graphs for HD engines are shown in Figure TS-5.

The top panel shows individual data points representing averages of each reported test (studies generally reported a range of emission rates for a given engine and fuel) at a given biodistillate level, and is color coded by pollutant species (NO_x, CO, PM and HC). To display the full range of observations, the y-axis spans a percent change of \pm 100%. A linear trend line for each species is included, which provides an assessment of the overall change in emissions with increasing levels of biodistillate.

The middle panel in Figure TS-5 collapses the data from the top panel by displaying the average of all test results at a given blend level vs. blend level. Error bars represent the minimum and maximum percent change from a reference diesel fuel for all test results at a specific biodistillate blend level. The bottom panel uses the same dataset as the middle panel, but displays a logarithmic trend line based on the average of all emissions for a given biodistillate level. This is the simplest way of showing the trend in emissions for each pollutant as a function of biodistillate level.

To compare the results of this analysis with findings of other studies, the regression equations derived from the logarithmic trendlines were used to predict the percent change in emissions of a given pollutant for a specified biodiesel blend level. These regression equations were determined for two different data sets:

- Full data set: includes results for all biodistillate fuels biodiesel and renewable diesel
- Biodiesel only data set: includes results from biodiesel, but not renewable diesel

Depending upon the engine type and pollutant species, the number of renewable diesel data points varied from 0 to 4. The blend levels of greatest interest are B20 and B100. Regression fits at these levels give the emissions changes shown below in Table TS-3.

	Pollutant	Full Data Set			Biodiesel Only Data Set		
	Pollutant	HD	LD	TE	HD	LD	TE
	NO _x	-0.3	+10.8	-8.1	-0.6	+10.8	-8.1
B20	CO	-16.6	-10.1	-13.4	-18.7	-10.4	-13.4
D2U	HC	-19.2	-16.6	-15.4	-21.2	-17.4	-15.4
	PM	-15.5	-14.6	-12.9	-24.1	-13.9	-12.9
	NO _x	+2.5	+15.3	-1.7	+3.0	+15.3	-1.7
B100	CO	-20.2	-12.3	-16.2	-23.2	-12.2	-16.2
БТОО	HC	-37.2	-22.9	-16.3	-40.4	-22.5	-16.3
	PM	-36.8	-31.7	-26.8	-42.2	-32.1	-26.8

Table TS-3. Predicted Changes in Emissions from 3 Engine Categories using B20 and B100

Notes: HD = heavy-duty and medium-duty CI engines

LD = light-duty CI engines

TE = single cylinder CI test engines



Averages of values reported within individual studies





Best fit curve based upon averages from individual studies



Figure TS-5. Effects of Biodistillate Blends on Exhaust Emissions from HD Engines

The B20 results for HD engines are further compared with those reported previously by EPA (2002) and NREL (2006) in Table TS-4. In large part, our results are consistent with these earlier reviews. For CO, HC, and PM, all three reviews show substantial emissions reductions from use of B20 (generally 10-20% reduction) with this study's results falling between the other two. NOx emissions results are less clear. EPA reported a 2.0% NOx increase with B20, while NREL reported a 0.6% increase (which was determined to not be statistically significant). In this study, the logarithmic data fit predicts a NOx change of near zero from use of B20.

	FΡΔ	McCormick	This Study		
Pollutant	2002	et al., 2006	Full Data	Biodiesel Only	
NO _x	+2.0	+0.6*	-0.3	-0.6	
CO	-11.0	-17.1	-16.6	-18.7	
HC	-21.1	-11.6	-19.2	-21.2	
PM	-10.1	-16.4**	-15.5	-24.1	

Table TS-4. Average Change in Emissions from HD Dynamometer Tests using B20

*Reported as statistically insignificant. **Excludes engines equipped with DPF.

Given the highly variable character of the reported emissions results, it is unlikely that any of the reported NOx effects in B20 blends are statistically significant. Also, the combination of many engine types, operating conditions, and fuel sources in our data sets makes interpretation of these emissions effects quite difficult. However, a more thorough statistical analysis of these results is beyond the scope of our study.

A graphical comparison of our emissions effects with those reported by EPA for the HD engine category is presented in Figure TS-6. While emissions reduction benefits for CO, HC, and PM seem quite clear (though perhaps smaller than previously believed), the NOx impacts remain small and uncertain.



Figure TS-6. Emissions Effects of Biodistillates from HD Dynamometer Tests

It has been suggested that biodistillate emissions effects may be sensitive to engine technology and operating condition. To explore this, the biodistillate emissions results reported in the literature were plotted vs. publication year, as a rough surrogate for engine technology. (Most publications do not clearly describe the engines with respect to model year, technology type, or certification level.) The NOx results for both B20 and B100 blends are shown in Figure TS-7. Given the limited results for each year, coupled with large error bars associated with most data points, it is difficult to draw quantitative conclusions. However, qualitatively it appears that the percent change in NOx emissions (for both B20 and B100) is largely unchanged with model year/technology.



Figure TS-7. NO_x Emissions for Biodistillate Fuels Compared to Reference Diesel Fuel

The same general results were observed for the other pollutants (CO, HC, and PM). No significant changes in emissions effects were apparent with changes in model year/technology. Furthermore, no clear distinctions could be seen between biodiesel and renewable diesel cases, although the number of data points for renewable diesel is very small.

The potential impact of biodistillate blends on emissions of toxic species was also investigated. The findings were limited, with most observations being for carbonyls -- particularly formaldehyde and acetaldehyde. Results for these species and total carbonyls are shown in Figure TS-8. Overall, the results imply there is a decrease in emissions with increasing blend level; although a number of studies reported increasing emissions for B20. This trend is somewhat surprising since biodiesel, which consists of oxygenated species (FAME), might be expected to increase aldehyde emissions. On the other hand, carbonyl formation from esters is not expected to be as facile as from alcohols or ethers.



Figure TS-8. Effects of Biodistillate Blends on Carbonyl Exhaust Emissions from HD and LD Engines

7. Life-Cycle Analysis and Land Use Impacts

In comparing energy and environmental impacts of different fuels, it is increasingly recognized that the entire life-cycle of the fuel must be considered. In fact, life-cycle models have become a common aid for policy regarding the use of alternative fuels. Life-cycle assessments (LCA) provide a tool to evaluate the energy and environmental impacts that result from all stages of a product's life, from manufacturing through disposal. Full fuel LCAs are commonly broken into two parts: (1) well-to-tank (WTT) and (2) tank-to-wheels (TTW). The combination of the two parts represents the complete well-to wheels (WTW), or "cradle-to-grave," life-cycle for a transportation fuel.

The WTT pathway for a biodistillate fuel commonly includes growth of the crop which may involve landuse change (LUC) and farming inputs like fertilizers, harvesting of the crop, processing or crushing to extract the oil, production (via transesterification or some other method), and distribution to the fueling station. The TTW analysis includes combustion of the fuel in a vehicle, and depends on the type of vehicle, its efficiencies, and type of driving. Common LCA practice for biofuels is to include only fossil carbon inputs. Thus, non-fossil carbon emitted during combustion of a biofuel is ignored (or offset) in the TTW portion of the life-cycle. This is sometimes referred to as the "carbon neutral principal," since the carbon being emitted is the same carbon that was recently absorbed by the biomass during its growth. With this assumption, the WTT results for GHG emissions of biofuels are similar to the complete WTW results.

Although established databases and modeling tools exist, differences in LCA modeling approaches are still common. Two models can be run with the same types of assumptions, yet produce different results. Standards have been developed to maintain some consistency in data. For example, ISO 14044:2006 provides modeling requirements and guidelines, and ISO 14048:2002 outlines standards for data documentation and format within the model. However, the standards do not specify methodologies that should be used, so results of different assessments can be highly variable. Therefore, fuel LCA models are typically used to determine the relative benefits of different scenarios in which conventional petroleum fuels are displaced with alternative fuels.

Differences in methodologies arise from variations in defining fuel pathways, scenario boundaries, input assumptions, and dealing with co-products. Most LCA data inputs are specific to the process, fuel type, or region that is being evaluated. For example, crop yields can vary dramatically based upon type of crop or growing location; also, energy use for a 2nd Generation production process may not be well established and must be estimated from scant data.

The demand for additional crops to support a biofuel industry could result in creation of new agricultural regions, as well as the conversion of exiting agricultural lands to new uses. This topic of land use change (LUC) and the way that it is considered (or not considered) in LCA modeling have drawn considerable attention recently. Both direct and indirect LUC may have significant impacts on the overall life-cycle results for a particular fuel. Direct LUC impacts are associated with the cultivation of feedstocks used to produce a biofuel in the region where it is used. Indirect LUC effects are those that could potentially arise when a crop is produced in one region of the world in response to fuel demand changes in another region.

Most LCA models include some type of direct LUC assessment to address changes in GHG emissions resulting from modifications to soil carbon, or variations in above ground biomass from preparation of existing crop-lands or conversion to new crop-land. Methods of including direct LUC are somewhat controversial, specifically with respect to N₂O, a potent GHG produced by biological processes. Because small changes in N₂O can result in significant differences in global warming potential (GWP), it is crucial to account for all nitrogen inputs and outputs associated with cultivation -- including crop residues, fertilizers, nitrogen fixation, manure usage, deposition, gaseous losses, crop output, runoff, nitrogen transfer between co-rotated crops, and others. Variations in assumptions about N₂O can swing the final GWP results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

Indirect LUC has been a topic of recent publicity and concern as having potentially serious adverse GHG impacts. As crops are diverted to fuels in one geographic location, increased crop production could be required elsewhere to compensate. This increased production could occur through displacement of existing crops, expansion of croplands, or intensification of existing production. Expansion of croplands may require reducing forest lands or other fallow lands elsewhere, which could result in an extremely large release of CO₂ previously sequestered by roots and soil. Intensification of production may require more fertilizer usage. Both could have a net-negative GHG effect for a particular biofuel. Most LCA models do not include the effects of indirect LUC because these effects are much more difficult to analyze and require subjective assumptions that contain substantial uncertainty. However, policy is trending toward including indirect LUC into already required LCA models. To do this, some type of economic model is required to estimate the economic supply and demand of developing new crop lands.

Another major source of variation among LCA results is the method by which co-products are treated. Several by-products are produced during the manufacturing of biodiesel; for example, animal feed meal is produced during the oil extraction process, and glycerol is produced during transesterification. Coproducts such as naphtha or propane may be produced in 2nd Generation biodiesel manufacturing involving catalytic hydroprocessing. Common practice in LCA modeling is to allocate some of the energy and emissions produced during the fuel life-cycle to these co-products since they can replace other similar products in the market. At least four different allocation methods are commonly used:

- Physical allocation
- Economic allocation
- Expanded allocation
- No co-product allocation

The choice of allocation method is controversial and not clearly defined. As with LUC, variations in coproduct allocation can also swing the final LCA results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

The life-cycle energy use required to produce and/or use a unit of fuel is one of the impacts most frequently assessed in an LCA. The overall energy benefit or energy return (ER) of the entire process is determined by dividing the energy out of the process (the heating value of the fuel) by the total life-cycle energy inputs. A net energy benefit results when the ER is greater than one; an ER less than one indicates more energy is required to produce the fuel than is contained in the final product. [This value of ER is sometimes called Energy Return on Investment (EROI).] Common practice in biofuel LCA is to include only fossil energy inputs in the ER calculation, but not any renewable energy inputs, such as the energy content of the plant itself. This typically results in an ER greater than one for biodistillates. In contrast, the energy requirements to make conventional diesel are almost entirely fossil energy, (including the energy content of petroleum itself) which typically results in a life-cycle ER of slightly less than one.

ER results for 19 literature reports are depicted below in Fig. TS-9. Very large ranges of results are shown for some studies which included several scenarios or sets of assumptions. In most cases, biodistillates showed a significant increase in ER compared to conventional diesel fuel. This is true for both biodiesel and renewable diesel scenarios. An overall average ER value from all the studies is approximately 3.1. Information such as this is the basis of claims that biodistillates offer a 3-fold improvement in energy return compared to petroleum diesel.

In LCA analyses of transportation fuels, GHG results are generally aggregated and reported on the basis of total global warming potential (GWP). To do this, emissions of all GHGs are converted to a CO_2 -equivalent basis using factors recommended by the IPCC or some other organization. Typically, the final GWP results are reported as grams of CO_2 -equivalent GHG emissions per MJ of fuel. Direct comparison of results among different studies should be done with extreme care, since different studies vary significantly in their assumptions and pathways. Of the numerous literature studies that reported life-cycle GHG impacts, most computed final GWP results in the range of 10 to 60 grams of CO_2 -equivalent emissions per MJ of fuel produced. The range of conventional diesel GWP values reported in these studies was from 22 to 240 grams of CO_2 -equivalent emissions per MJ of fuel.

A somewhat more instructive way to compare results among different LCA studies is to evaluate differences between the biodistillate and conventional fuel scenarios within each study. On this relative basis, most LCA studies report that biodistillate scenarios result in 10-90% lower GWP compared to a conventional diesel baseline. Similar benefits are seen for both biodiesel and renewable diesel cases, from a variety of feedstocks. However, as shown in Fig. TS-10, many of these studies include wide ranges of results, resulting from different assumptions and approaches. Study No. 34, which showed a significant dis-benefit for biodiesel, utilized much higher N₂O emissions than most other studies. This clearly illustrates the sensitivity of LCA results to input assumptions.
Energy Return



Figure TS-9. Energy Return for 19 LCA Models (Study No's identified in Appendix VI)

In addition to GWP and energy requirements, other ecological or resource impacts are often assessed using LCA methodologies. Some of the most important impact categories pertain to water resources, eutrophication, acidification, and photochemical ozone creation potential. However, compared to GWP and energy impacts, assessments of these other life-cycle impacts are still in their infancy.







8. Summary and Conclusions

The major results and conclusion from this review of biodistillate topics are summarized below:

Policy Drivers

- Many countries have developed policies to promote greater production and use of biodistillate fuels. The U.S. Energy Independence and Security Act (EISA) of 2007 requires 0.5 bg/y of biodiesel by 2009, and 1.0 bg/y by 2012. Even more aggressive targets are set by Europe and several other countries.
- Taken together, the policy-driven volumetric requirements of the U.S., Europe, China, India, and Brazil total 23 bg/y by 2020. However, unless additional feedstocks are identified, and the economic situation improves, considerably lower volumes may be expected within this time frame.

Biodiesel Volumes and Feedstocks

- While numerous triglyceride feedstocks have been investigated as potential feedstocks for biodiesel production, only a few are in widespread commercial use. The dominant feedstock in the U.S. is soybean oil, with far lesser amounts of other seed oils, used cooking oils, and animal fats being used. In Europe, the dominant feedstock is rapeseed oil.
- Biodiesel production capacity has grown much faster than actual production volumes, and excess capacity has become a serious problem within the biodiesel industry. This is driven by limited availability and high costs of current feedstocks. Consequently, there is great interest in developing alternative feedstocks, particularly those that do not have concurrent uses as food. Two of these so-called, 2nd generation feedstocks receiving considerable attention are jatropha and microalgae. It is likely that commercially produced biodistillates from these feedstocks will begin to appear in the marketplace within the next 5 years.
- In most locations, the predominant use of biodiesel is as a low-concentration blend with petroleum diesel. Concentrations of 2% (B2), 5% (B5) and 20% (B20) are most common. Only in Germany and Austria is neat biodiesel (B100) commonly employed as a transportation fuel.

Biodistillate Production Technology

- The dominant biodiesel production technology in commercial use involves transesterification of triglyceride feedstocks (from fats and oils) with methanol to produce fatty acid methyl esters (FAME). This process also results in production of low-purity glycerol, which must be upgraded or otherwise disposed. Process improvements involving co-solvents, better catalysts, and alternative heating methods are being actively investigated.
- Catalytic hydroprocessing of triglycerides is an alternative route to biodistillates that does not involve alcohols or glycerol production. The product of this process is commonly known as renewable diesel, as opposed to biodiesel. Renewable diesel consists of hydrocarbons that are virtually identical to those found in petroleum diesel. Production of renewable diesel is most conveniently accomplished within an integrated petroleum refinery.

Fuel Properties and Specifications

• The properties of biodiesel are largely dictated by the chemical composition of the fatty acid methyl esters comprising the fuel. Two of the most important chemical parameters affecting the overall fuel properties are carbon chain length and degree of unsaturation (carbon-carbon double bonds) within the FAME molecules.

- Biodiesel typically contains about 11% oxygen, in the form of methyl esters. As a consequence, it has lower mass energy content than petroleum diesel by about 10%. Renewable diesel, containing no oxygen, has a mass energy content very similar to petroleum diesel.
- Standard specifications for biodiesel fuel have been developed, and are continuing to evolve. In the U.S., biodiesel (B100) specifications are defined by ASTM D 6751; European specifications are defined by EN 14214. Specifications for biodiesel blends are also being developed. ASTM D 7467 applies to B6 B20 blends with ULSD; EN 590 now permits blends up to B5.
- Biodiesel fuel standards include numerous specifications and test methods to ensure acceptable product quality and performance. Attaining full compliance with biodiesel standard specifications requires extensive and regular laboratory testing.

In-Use Handling and Performance

- Adhering to established quality control/quality assurance (QC/QA) measures is critical to ensuring satisfactory biodiesel quality in the marketplace. In the U.S., the BQ-9000 Quality Management System was recently developed to define acceptable QC/QA measures. BQ-9000 includes separate sets of requirements for B100 producers and B100 marketers.
- Past U.S. fuel quality surveys have shown significant inaccuracies of blending, with some reported B20 blends actually containing much more or much less than 20% biodiesel. These surveys also revealed problems with off-spec biodiesel in the marketplace. More recent surveys indicate that overall, product quality in the marketplace is improving.
- In general, biodiesel has somewhat poorer low temperature operability than petroleum diesel, though the extent of the difference varies substantially based upon the unique chemical composition of the biodiesel in question. Low temperature operability can be improved by proper selection of triglyceride feedstocks, greater dilution with petroleum diesel, use of cold flow improver additives, and use of ethanol rather than methanol in the transesterification process.
- While exceptions are possible, acceptable in-use handling and performance of biodiesel is best achieved by strict adherence to established fuel specifications and implementation of good fuel housekeeping practices. Additionally, to minimize concerns regarding fuel stability, viscosity, materials compatibility, and others, it is prudent to limit the biodiesel composition to B20 and below.

Exhaust Emissions

- Review of the literature indicates that in most cases, use of biodistillates, even at a B20 level, substantially decreases emissions of CO, HC, and PM generally by 10-20%. Although results vary considerably from one study to the next, these emissions benefits are typically seen in both LD and HD engines, regardless of engine technology or test cycle. Although data are much more limited for renewable diesel cases, it appears that similar benefits in reduction of CO, HC, and PM are observed with these hydroprocessed fuels.
- NOx emissions impacts are much smaller, and difficult to discern. Though highly variable, most studies indicate a slight NOx increase when using B100 fuel. For HD engines, our best estimates are that NOx emissions increase 2-3% with B100, but are unchanged from conventional diesel fuel for B20 blends. There are limited reports suggesting that use of renewable diesel provides a NOx emissions benefit compared to biodiesel. Further testing is necessary to confirm (or refute) this finding.
- Much less information is available regarding non-criteria pollutant emissions from use of biodistillate fuels. The pollutants most frequently reported are formaldehyde and acetaldehyde. The majority of published reports indicate a slight decrease in aldehyde emissions when using B20, and a larger

decrease when using B100. A more substantial body of emissions data is necessary to confirm (or refute) these observations.

Life-Cycle Analyses and Land Use

- Life-cycle assessments (LCA) of "well-to-wheels" energy inputs and GHG emissions are now recognized as important tools for understanding the relative benefits of biodistillate fuels compared to conventional fuels. However, LCA models are very data intensive, and require numerous inputs having high uncertainty. Some of the most critical inputs are in areas that are most uncertain such as assumed agricultural practices and their emissions, impacts attributed to co-products, and land use changes (LUC).
- Variations in LCA model assumptions have drastic effects on the final results. Consequently, it is difficult to compare directly LCA results from different studies. Two areas having large effects on final LCA outcomes are assumptions regarding LUC and co-product allocations. Because of significant variations in assumptions across different studies, comparison of relative effects between biodistillate fuel and conventional fuel scenarios conducted within the same study is often more informative.
- Most LCA models account for direct LUC, in which changes in cultivation, fertilizer use, and other agricultural practices occur to produce a biofuel in the region where it is used. However, no biodistillate LCA models to-date have accounted for indirect LUC, where agricultural practices in one region of the world are modified in response to fuel demand changes in another region. Assessment of indirect LUC requires the combination of economic models with LCA models.
- Life-cycle energy results are typically reported as energy return on investment (EROI, or more simply, ER), meaning the heating value of the final biofuel divided by the total fossil energy inputs involved in producing, distributing, and using the fuel. Typically, ER values for conventional diesel fuel are slightly under 1.0. Our analysis of 19 LCA studies gave an overall average ER value of about 3.1 for biodistillates, indicating substantial benefits for these fuels (both biodiesel and renewable diesel) in terms of life-cycle energy.
- LCA results for GHG emissions are usually expressed in terms of relative global warming potential (GWP). In almost every published LCA study, biodistillate scenarios resulted in lower GWP compared to conventional diesel. In most of the 24 studies we investigated, the GWP benefits of the biodistillate fuels ranged from 10% to 90%, with an overall average value of about 60%. However, there are a few exceptions, mainly due to assumptions of high N₂O emissions, where biodistillate scenarios showed overall GWP dis-benefits compared to conventional diesel.

1. Introduction and Background

In recent years, the production and use of biofuels have increased dramatically, both in the U.S. and around the world. This growth is driven by somewhat different factors from one country to the next, but the strongest factors generally include the following:

- National energy security
- Diversity of energy sources
- Concerns over greenhouse gases (GHGs) and global climate change
- Desire for sustainable energy sources
- Rural economic development
- Improved balance of trade

Over the past 10-20 years, most of the interest and activity regarding biofuels was focused on ethanol, and its use in light-duty gasoline vehicles (LDGV). While ethanol remains a topic of considerable interest and debate, recent years have seen rapid growth in activities pertaining to biofuels meant for blending with diesel fuel and used in vehicles with compression ignition (CI) engines.

Numerous aspects of biofuels are of interest and importance – including feedstocks, production technologies, fuel properties and standards, vehicle emissions, fuel performance and handling, and lifecycle impacts. Due to the evolving nature and rapid growth of information in these areas, CRC wished to conduct a study to assess the state-of-knowledge regarding plant- and animal- derived biofuels as blending materials for ultra-low sulfur diesel (ULSD) fuel in transportation applications. This report documents our efforts to meet these objectives, and provides a summary of the information we believe to be most pertinent to CRC's interests.

1.1 Limits of Study

Although CRC's primary interest relates to plant- and animal- derived biofuels used in ULSD, it is useful to expand the scope of the study somewhat, to provide greater context for this particular area of focus. For example, ULSD – meaning 15 ppm sulfur level – is a fuel designation exclusive to the U.S., and has been in common usage only since 2006. Thus, while our study does emphasize recent information pertaining to ULSD blend applications in the U.S., we also consider use of neat biofuels (B100), biofuel blends in non-ULSD diesel fuels, and use of biofuels and blends in other countries.

In addition to plant- and animal- derived feedstocks, there is also considerable interest in converting lignocellulosic feedstocks into biofuels. For production of mid-distillates, thermal processes involving gasification and pyrolysis are being developed.^(1,2) However, as these areas of development are evolving rapidly – and largely involve proprietary information – this report will not emphasize the production of mid-distillate biofuels from lignocellulosic feedstocks.

It is also important to point out what biofuels topic areas will not be covered in this report. With the emphasis on diesel applications and ULSD blends, we do not consider ethanol (or other alcohols) intended for use in spark-ignition (SI) engines. Other topics excluded from this study include the following:

- Mid-distillate fuels used in non-transportation applications (turbines, boilers, other stationary sources)
- Theoretical or fundamental studies of combustion chemistry, kinetics, and modeling
- Analytical methodologies for detecting and characterizing biodistillates

- Toxicity and health impacts of emissions
- Agriculture, agronomy, and food science studies
- Social, political, or economic studies

1.2 Definitions

Before proceeding, it is important to define fuel-related terminology that is commonly used within the fuels and automotive industries, and is incorporated into this report. A detailed list of common abbreviations and acronyms is provided near the end of this report in Section 13. Some of the most frequently used transportation fuel terms are shown below in Table I. A more complete glossary of fuel terms is provided in Appendix I.

Certain biofuel terminology requires further explanation. In this report, we use the term "biodistillate" to designate all common mid-distillate fuels (diesel, kerosene, jet fuel, and heating oil) that are produced from biological feedstocks – including animal fats, vegetable oils, and lignocellulose. Thus, "biodiesel" and "renewable diesel" are both subsets of "biodistillates." They are usually described together, except when distinctions are made regarding differences in production technologies, fuel properties, or performance.

Biodiesel is defined by ASTM as "a fuel comprised of mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats, designated B100." ⁽³⁾ Congress has adopted a similar definition for "Biomass-based diesel," with the additional requirement that the fuel have life-cycle greenhouse gas emissions that are at least 50% less than baseline life-cycle greenhouse gas emissions. ⁽⁴⁾ Unless otherwise indicated, the term "biodiesel" refers to neat material – i.e. B100. Lower concentrations, such as B20, are properly referred to as "biodiesel blends," not biodiesel itself.

Terminology regarding "1st Generation" and "2nd Generation" biofuels also requires clarification. Although these terms are in common usage, they have no legal or regulatory meaning. Generally, the term "1st Generation" refers to biofuels produced from commonly available, edible feedstocks using wellestablished conversion technologies. Most biofuels in use today are classified as 1st Generation. This includes ethanol produced via fermentation of sugars (from corn, sugar cane, sorghum, etc.) and biodiesel produced via transesterification of triglycerides (from vegetable oils and animal fats).

The term "2nd Generation" can refer to biofuels produced from either advanced, non-food feedstocks, or produced via advanced processing technology (or both). Examples of advanced feedstocks include lignocellulose and non-edible triglycerides (such as jatropha and algae). Examples of advanced processing technology include catalytic hydroprocessing of triglycerides and thermal conversion (gasification and pyrolysis) of lignocellulose.

In this report, which is focused on biodistillate fuels, we use the term 1st Generation to refer to biodiesel produced via transesterification of edible triglycerides (including waste cooking fats and oils). The term 2nd Generation is used to refer to Renewable Diesel, Green Diesel, and biodiesel produced via transesterification of non-edible triglycerides. To avoid confusion about variable meanings, the term "3rd Generation" (or other similar terms) is not used in this report.

1 st Generation Biofuels	Fuels produced from commonly available, edible food feedstocks via fermentation (such as grain to ethanol) or transesterification (vegetable oil to biodiesel).
2 nd Generation Biofuels	Biofuels produced from non-food feedstocks (such as jatropha, algae, and lignocellulose) by any processing technology, or from edible feedstocks using advanced conversion processes (such as catalytic hydroprocessing).
Alternative Fuel	Any fuel produced from non-petroleum sources. Includes biofuels as well as liquid fuels produced from coal and natural gas.
Biodiesel	Fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oil or animal fats.
Biodistillate	Any mid-distillate fuel (diesel fuel, kerosene, jet fuel, or heating oil) produced from recently living plant or animal materials by a variety of processing technologies.
Biofuel	Fuel produced from recently living plants or animals. This includes gases, liquids, and solids produced via fermentation, digestion, enzymatic hydrolysis, thermal conversion, and other processes.
Cellulosic Fuel	Subset of biofuel, produced from lignocellulosic feedstocks.
Clean Fuel	Ill-defined, colloquial term having variable meanings. Often used in regulatory language.
Conventional Fuels	Any fuel produced from petroleum sources.
Fossil Fuel	Fuel produced from fossil resources – including coal, petroleum, and natural gas.
Green Diesel	Non-fossil hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats. Synonymous with Renewable Diesel.
Renewable Diesel	Non-fossil hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats. Synonymous with Green Diesel.
Renewable Fuel	Gas, liquid, or solid fuel produced from modern biologic feedstocks (plants and animals) that can be replenished.
Synthetic Fuel	Liquid fuel, produced from non-petroleum resources, generally via gasification and subsequent reaction of the synthesis gas.

Table I. Definitions of Common Transportation Fuel Terms

Note: For a more complete glossary of fuel terms, see Appendix I.

1.3 Information Sources

Much of the effort in this study consisted of a thorough review of the technical literature regarding the feedstocks, production technologies, properties, characterization, testing, performance, and environmental impacts of biodistillate fuels. An excellent starting point for information on all these topics is *The Biodiesel Handbook*,⁽⁵⁾ published in 2005. This handbook consists of numerous chapters on these individual topics, written by experts in each area.

With the field of biodistillates being fairly young, our literature search focused on recent years (2000 to the present) though selected older items of interest were also reviewed. The principal sources used to locate the relevant literature are the following five:

1. Web of Science: Used to search peer-reviewed publications in over 6000 scientific journals/periodicals.

- 2. SAE literature search engine: Used to search literature published by the Society of Automotive Engineers, International (SAE).
- 3. ASME literature search engine: Used to search literature published by the American Society of Mechanical Engineers (ASME).
- 4. DOE citation database: Used to search DOE reports and other DOE-sponsored work reported in conference presentations and technical reports.
- 5. Trade literature, patents, and other sources: Web sites of trade organizations, fuel producers and marketers, governmental agencies, and other relevant entities were searched to obtain additional information of interest. Also, a few patents of particular interest were reviewed.

The general approach was to begin with broad search terms such as "renewable diesel" and "biodiesel," then use an iterative process to exclude those items of little or no interest. For example, most pamphlets and presentations were excluded, as well as most foreign-language items. Further screening and elimination was done based upon a review of titles and abstracts. Through this process, we reduced the items of interest to approximately 1000.

The first step in organizing the literature was to compile all relevant citations using a Thomson ResearchSoft computer program called Reference Manager. Literature sources identified by the Web of Knowledge search tool were directly downloaded into Reference Manager. However, sources identified through the SAE, ASME, or DOE databases required manual entry into Reference Manager.

Based primarily upon review of abstracts, we constructed a reasonably comprehensive bibliography of literature that is relevant for this study. In the process, we identified specific biodiesel/renewable topics that were discussed in each literature report. The topic categories were selected to correspond to the organizational structure of this final report, including the following 6 areas:

- 1. Feedstocks
- 2. Fuel production technology
- 3. Fuel properties and specifications
- 4. Vehicle emissions
- 5. Fuel handling and performance
- 6. Life-cycle analysis

The final bibliography was constructed as an Excel Worksheet, and is included here as Appendix II. This spreadsheet approach enables the reader to sort the information by author, date, or topic area. Many of the 1000 items in this bibliography are of minimal relevance to CRC's interests, but are included for the sake of completeness.

The reader will note that in addition to the 6 topic areas mentioned above, some of the literature reports listed in Appendix II include discussions of economics and fuel policy. In this project, no deliberate effort was made to search the literature for these additional topics; rather a few literature sources identified in our search for the main 6 topic areas also contained ancillary information about economics and policy. We merely include this information here as an additional item of interest. This report should not be considered to provide a thorough review on the topics of economics and fuel policy of biodistillates.

Perhaps more useful to the reader is the much smaller bibliography subset indicated by the shaded entries in Appendix II. This subset contains about 50 items that we have judged to be the most important for gaining a thorough understanding of the biodistillate technical topics of greatest interest to the automobile and fuels industries.

It should be emphasized that the subject areas related to biodistillate fuels are currently very active, with about 20-30 new items of interest appearing in the literature each month. Because of this rapid expansion of information, we updated our search several times throughout the course of this study. Our final complete literature search update was conducted on September 30, 2008. The reader should be aware that numerous additional, relevant publications have appeared since that time.

As shown below in Fig. 1, most literature of interest is very recent. Over 75% of relevant journal papers -- and 75% of SAE papers -- have appeared within the past 3 years. In this figure, the category called "Papers" consists mainly of SAE and ASME papers. The category called "Reports" consists mainly of governmental reports (especially from DOE) and company publications. The largest category, called "Journals," consists of peer-reviewed papers appearing in dozens of different science and engineering periodicals.



Figure 1. Biodistillate Fuel Publications by Year

2. Policy Drivers for Biodistillate Fuels

2.1 U.S. Federal

In the U.S., the current dominant policy driver for biodistillate fuels is the recently enacted Energy Independence and Security Act of 2007 (EISA).⁽⁴⁾ (Prior to EISA, the main driver for biodistillates was the \$1/gallon blenders' tax credit.) Through EISA, for the first time, Congress has established specific, volumetric requirements for biomass-based biodiesel of 500 million gallons/year (mg/y) by 2009, ramping up to 1 billion gallons/year (bg/y) by 2012. With current on-road diesel fuel usage in the U.S. at approximately 40 bg/y; the maximum EISA biodiesel requirement represents about 2.5% of this total. Though still not determined, it is possible that EPA will adopt an "energy content multiplier" for biomass-based diesel, whereby each physical gallon is credited as 1.5 gallons in meeting the renewable fuel standard (RFS) within EISA. If this multiplier approach is used, the 1 bg/y biodiesel mandate will only require 0.67 bg/y of actual use.

EISA also establishes a total RFS requirement of 36 bg/y, to be met by 2022, with 21 bg/y of this coming from "advanced biofuels," meaning fuels derived from renewable biomass (excluding ethanol derived from corn) that achieve at least a 50% reduction in GHG emissions, on a life-cycle basis. Biodiesel and

renewable diesel may both qualify as "advanced biofuels," though this determination has not yet been finalized. Figure 2 shows the U.S. renewable fuels production requirements stipulated in EISA, as well as the earlier requirements under the 2005 Energy Act. Also shown in this figure are historical production volumes of ethanol and biodiesel from 1999 to 2007.



Figure 2. U.S. renewable fuels production and Energy Act requirements (Taken from Reference No. 1)

Numerous other federal incentive programs exist to promote greater use of biodiesel. Many of these are voluntary, with relatively little participation. Some of the better known programs include the following:

- Clean School Bus USA
- Clean Construction USA
- Clean Agriculture USA
- Clean Fuels Grant Program
- Clean Cities Program
- Biobased Products and Bioenergy Program

These and many other federal initiative programs are summarized by the Alternative Fuels and Advanced Vehicle Data Center, and posted on their website.⁽⁶⁾

2.2 U.S. States

Several U.S. States have also established policies to promote greater use of biodiesel. One of the most aggressive states is Minnesota, which established a statewide B2 requirement in 2005.⁽⁷⁾ More recently, Minnesota has adopted a measure that will require increasing from B2 to B20 by 2015.⁽⁸⁾ Due to difficulties experienced in meeting the earlier B2 requirement, the current B20 plan incorporates several safeguards and checkpoints. It remains to be seen whether the B20 standard is achievable within the designated timeframe. The State of Washington has also adopted a Renewable Fuels Standard that requires 2% biodiesel state-wide, beginning in 2009.⁽⁹⁾

California is also actively promoting increased use of biofuels. As early as 2000, California passed legislation requiring investigation of ways to reduce the State's petroleum dependence.⁽¹⁰⁾ In response to this, the California Energy Commission (CEC) and the California Air Resources Board (CARB) prepared a joint agency report that recommended increasing alternative fuel usage to constitute 20% of total onroad transportation fuels by 2020, and 30% by 2030.⁽¹¹⁾

Subsequently, California Bill AB-1007 required CEC and CARB to "develop and adopt a State Alternative Fuels Plan (AFP) to increase the use of alternative fuels" in California.⁽¹²⁾ This AFP must establish specific goals for alternative fuel usage in 2012, 2017, and 2022. Furthermore, CEC and CARB are required to conduct Full Fuel-Cycle Analyses (FFCA) of the alternative fuels proposed in this plan, and ensure "no net material increase in air pollution, water pollution, or other substances known to damage human health." The California AFP has now been developed, and calls for the total alternative fuel volumes shown below in Table II.⁽¹³⁾ Biodiesel and renewable diesel are two of the specific biofuels included in this AFP, though there are no specific volumetric requirements for them.

Year	Alternative Fuel Volume, bg/y	Reduction of Conventional Fuels, %
2012	2.4	9
2017	3.7	11
2022	5.3	26
2030		30
2050		50

Table II. Goals Included in California's Alternative Fuels Plan

Currently, CARB is conducting an experimental program with biodiesel and renewable diesel to ensure compliance with the AB-1007 requirement of no harm.⁽¹⁴⁾ This program includes detailed engine laboratory work to investigate the emissions impacts of using blends of biodiesel and renewable diesel in petroleum diesel. NOx emissions are of particular interest. This CARB study will also investigate several strategies for mitigating the NOx increase that is anticipated from use of biodiesel.

California is also developing a Low Carbon Fuels Standard (LCFS)⁽¹⁵⁾ and has recently passed legislation (AB-32) to address global warming concerns.⁽¹⁶⁾ AB-32 goals require statewide reduction of GHGs to achieve the 2000 level by 2010, the 1990 level by 2020, and 80% below the 1990 level by 2050. These reductions will be based upon "life-cycle values" by a mechanism that is just now being defined.⁽¹⁷⁾ Meeting California's LCFS and GHG reduction goals will require various aggressive measures, including extensive use of biofuels.

Very recently, Massachusetts adopted legislation, the Clean Energy Biofuels Act, that mandates inclusion of biodiesel in all diesel fuel and heating oil.⁽¹⁸⁾ The biodiesel fraction begins at 2% in 2010, and then increases by an additional 1% absolute per year until reaching 5% in 2013. In addition, this legislation requires Massachusetts to develop a LCFS (similar to California's) that would reduce GHG emissions from the transport sector by 10%.

In Illinois, state tax policy has prompted use of a unique biodiesel blend, B11. According to the 35 ILCS 105 Use Tax Act, biodiesel blends above B10 are granted preferential tax treatment.⁽¹⁹⁾ To take advantage of this situation, use of B11 has become quite common in Illinois.

2.3 Europe

Biodiesel has been produced and used in Europe to a much larger extent than in any other location – particularly in Germany, France, and Italy.^(20,21) While each country has its own policies and incentives, broad European Union (EU) policies have also been established. In 2003, EU Directive 2003-30-EC established targets for biofuels content of transportation fuels.⁽²²⁾ According to this directive, biofuels must constitute 2% of transport fuels by 2005, and grow by 0.75% absolute per year until reaching 5.75% in 2010. These requirements apply to all transportation fuels, not just diesel fuel, though 75-80% of the requirement is being met by use of biodiesel. Approximately 20% of the EU biofuels requirement is

currently being met with bioethanol, and the small remainder is being met with straight vegetable oil (SVO).⁽²³⁾

The EU has also defined a "benchmark" of achieving 20% biofuels by 2020, though there is no legally binding requirement for this. At present, this 20% benchmark seems unattainable, and is not being vigorously pursued by the EU. A reduced target of 10% biodiesel by 2020 has been proposed and is now being discussed within the EU, though at present, there is no legally binding requirement to meet this target either.

2.4 Other Countries

Many other countries around the world are beginning to develop policies to promote greater use of biodiesel.⁽²⁴⁾ Those of particular note are Brazil, China, and India.⁽²⁵⁾ In 2004, Brazil enacted a National Biodiesel Production Program (PNPB) which established a mandate for all petroleum diesel fuel to contain biodiesel by 2008.⁽²⁶⁾ Later legislation in 2005 (Federal Law 11.097 and Decree 5448) defined the requirement of 2% biodiesel by 2008 (estimated to be 222 mg/y) and 5% biodiesel by 2013 (estimated to be 634 mg/y).

China recently established a Renewable Energy Law which calls for biodiesel consumption of 2 million tons/year (mt/y; approx. 600 mg/y) by 2020.* An interim goal of 0.2 mt/y (approx. 60 mg/y) by 2010 is also in place. These current goals are much less aggressive (by an order of magnitude) compared to the biofuels targets that China had set previously (3 bg/y by 2010; 5 bg/y by 2020). A major reason for this less aggressive stance is China's concern about food security, and the potential competition between food and fuel uses of vegetable oil feedstocks.

In India, the Central Government developed a "National Mission on Biodiesel" in 2003. Subsequently, a detailed project report was developed to lay out a national plan for promoting increased production and use of biodiesel. This plan emphasizes greatly increased cultivation of jatropha curcas, and use of its seed oil as a biodiesel feedstock. The government also established a target of 5% biodiesel by 2007 (estimated to be 0.78 bg/y), with a longer term goal of 20% by 2020 (estimated to be 6.71 bg/y).

The nominal sum of these policy-driven biodistillate volumetric requirements is approximately 23 bg/y, as shown in Fig. 3. However, for several reasons, we believe these values greatly overestimate the actual amounts of biodistillates that will exist in the marketplace over this period of time. The rationale for our more conservative estimates is explained below for each of the major geographic regions discussed above:

- <u>Europe</u>: Europe is currently satisfying its 2005 biofuels requirement content of 2%. However, due to severe feedstock shortages and high prices (described in the next section) we do not expect Europe to meet the 5.75% biofuels requirement until 2012 (rather than 2010). After that, we anticipate slow growth of 2% per annum (resulting mainly from increased imports of biodistillates) reaching a level of 3.51 bg/y in 2020. This amount of biodiesel will represent 6-7% of Europe's total transportation fuel usage in 2020.
- <u>U.S.</u>: We expect the U.S. to achieve the 1.0 bg/y biodiesel requirement included in the 2007 EISA. However, lacking any additional legislative action, we expect this level will remain relatively flat through 2020, with any additional production being exported to help satisfy other countries' requirements. It is also possible that some additional U.S. production will be used to help satisfy the EISA requirement of 21 bg/y of advanced biofuels.

^{*} In most countries outside the U.S., biodiesel production and usage requirements are expressed as million metric tonnes per year (mmt/y). In this report, we have converted all mmt/y values to U.S. volumetric values of mg/y. Assuming a specific gravity of 0.88 for biodiesel, 1 metric tonne equals 300 U.S. gallons.

- <u>Brazil:</u> We believe that Brazil will meet its goals of 2% biodiesel by 2008 and 5% biodiesel by 2013. Beyond this, we anticipate a 2% per annum growth rate in biodiesel volume used in Brazil. From this, we project a 2020 level of 0.73 bg/y.
- <u>China:</u> China originally established a very aggressive biodiesel goal of about 5 bg/y by 2020. (These original values are reflected in the projections shown in Fig. 3, because we believe they still represent the official Chinese position.) However, recent modifications have been announced, which reduce the volumetric requirements by about an order of magnitude, to 60 mg/y by 2010 and 600 mg/y by 2020. While much less aggressive than previously, achieving the new goals still requires a growth rate of 25% per annum from 2010 to 2020, which may be quite difficult to maintain.
- <u>India:</u> India's currently stated biodiesel goals are extremely aggressive. Reliable figures are difficult to obtain, but it is clear that India is not close to meeting its 2007 goal of 5% biodiesel. We expect that India will follow the same path as China, and will announce dramatically reduced biodiesel goals in the near future. Assuming India achieves 2% biodiesel usage in 2010, and then grows by 10% per annum, it will reach a total of 1.01 bg/y by 2020.



Figure 3. Policy-Driven Volumetric Biodiesel Requirements

The sum of our five regional biodistillate projections is 6.51 bg/y by 2020. This is far less than the nominal regulatory requirement of 23.4 bg/y shown in Fig. 3, but still represents a 2.5-fold increase from today's actual production level. Achieving this projected 2020 level of 6.51 bg/y will require an annual growth of about 8%.

3. Biodiesel Volumes and Feedstocks

In recent years, the growth of biodiesel production and use around the world has been dramatic, though exact figures are somewhat difficult to obtain and confirm. In this section, we summarize information gleaned from global market surveys (especially Biodiesel 2020⁽²⁵⁾), industry web sites (especially NBB⁽²⁷⁾ and EBB⁽²⁸⁾), and other published sources to present a picture of current and future fuel volumes and feedstocks.

3.1 Current/Conventional Feedstocks

While alternative feedstocks are now beginning to receive some attention, the only biodistillate feedstocks used commercially to-date have been triglycerides from animal fats and seed oils. Thus, this report will emphasize these conventional biodiesel feedstocks, while including some discussion of alternative feedstocks.

Figure 4 presents an overall summary of biodiesel production around the world. Clearly, Europe has been – and continues to be – the dominant region for biodiesel. This is also evident by comparing the number of biodiesel plants in Europe and the U.S., as shown in Fig. 5.

In Europe, the dominant biodiesel feedstock is rapeseed oil, while soybean oil dominates in the U.S. However, increasing diversity in feedstocks is occurring globally, as the demand for conventional feedstocks is beginning to exceed supply, and producers are seeking alternative. less expensive feedstocks. In addition, many other oil-bearing plants are now being investigated commercially (or semicommercially), with several offering the possibility of greater yields than the conventional rapeseed or soybean. This is illustrated below in Table III. Of course, actual yields will vary depending upon soil type, water availability, fertilizer use, climatic conditions, and other factors.



Figure 4. Global Growth in Biodiesel Production



Figure 5. Growth in Number of Biodiesel Plants

Source	Potential Yield, gallons/acre	Source of Info (Reference Nos.)	
Corn	18	(29,30,31)	
Soybean	40-55	(25,29,30,32,31)	
Canola (Rapeseed)	110-145	(25,29,30,31)	
Sunflower	102	(30)	
Safflower	83	(29)	
Cotton	35	(30)	
Mustard	60-140	(25)	
Jatropha	175-200	(25,30,31)	
Coconut	290	(31)	
Palm Oil	600-650	(25,29,30,31)	
Algae	>5000	(25,29,31)	

Table III	Potential	Biodistillate	Output
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3.1.1 Europe

According to the European Biodiesel Board (EBB), in 2008 there were 185 fully operational biodiesel plants in the EU, with another 58 under construction. Europe has dominated the global biodiesel industry to-date, with approximately 80% of global production. Currently, the overall share of biodiesel in the European diesel pool is between 2 and 3%, though the EU goal is to reach a level of 5.75% by 2010. (The 5.75% biofuels goal applies to all transportation fuels – including gasoline – though 75-80% of European biofuels today is in the form of biodiesel.)

The top three European producers of biodiesel are Germany, France, and Italy, though nearly every EU country has some production, as shown in Fig. 6. ^(25,21)



Figure 6. European Biodiesel Production by Country - 2007

While European biodiesel production has been growing, production capacity has grown even faster. This is illustrated in Fig. 7, which shows that in 2007, capacity was twice as large as production. This underutilization of capacity became even more severe in 2008, as difficulties with feedstock supply and cost occurred, and biodiesel tax incentives were reduced.

These problems are most severe in Germany, where current capacity utilization is reported to be below 25%. Until 2006, B100 was sold "tax free" in Germany. With the phase-out of this and other financial incentives, the cost of biodiesel has risen dramatically and the demand has dropped. Also, of all the EU countries, Germany and Austria are the only ones where B100 is in widespread use. In all other countries, lower level blends (B2, B5, and B20) are much more common.⁽³³⁾



Figure 7. European Biodiesel Capacity and Production

The dominant feedstock for European biodiesel is rapeseed -- a close relative of canola, which is used in the U.S. -- with sunflower seed being a distant second. Despite agricultural incentives and use of set-aside lands for rapeseed cultivation, the amount grown is insufficient to satisfy the goal of 5.75% biofuel by 2010. To help meet this policy-driven mandate, Europe has imported significant volumes of biodiesel in recent years – both from the U.S. (soybean-based) and from Southeast Asia (palm-based). However, due to concerns about sustainability, biodiversity, and GHG emissions, the EU's Environmental Committee amended their fuel quality directive in late 2007 to ensure that biofuels must meet strict environmental goals.⁽²³⁾ In effect, this will restrict the importation of palm oil from Southeast Asia.

Feedstock supply is expected to limit Europe's biodiesel production to well below the 5.75% goal by 2010.⁽³⁴⁾ The reliance upon rapeseed as feedstock has now become very restrictive, as the supply is far less than the demand, leading to very high feedstock costs. (80% of total biodiesel cost is attributed to feedstock.) Even in Germany, which is the European leader in biofuel production, it is clear that not enough rapeseed can be grown to meet its needs. Other, lower-cost feedstocks (such as yellow grease and tallow) are beginning to be used, but their availability is also very limited. For continued growth of the European biodiesel industry, significant new feedstocks are required, such as algal oils and biomass-to-liquids (BTL) products.

3.1.2 U.S.

According to the National Biodiesel Board (NBB), at the end of 2008 there were 176 operational plants in the U.S., with several others under construction. The locations of these plants are shown on the map in Fig. 8 (taken from the NBB website).



Figure 8. Location of U.S. Biodiesel Plants - 2008

Total U.S. diesel fuel consumption is currently approximately 60 bg/y, with 40 bg/y of this being used for on-road transportation applications. U.S. biodiesel production in 2007 was approximately 450 mg/y, or about 1.1% of the on-road diesel volume. However, much smaller volumes of biodiesel were actually consumed in the U.S., as at least ½ of U.S. produced biodiesel was exported to Europe.⁽²⁵⁾ With phase-in of the U.S. EISA requirement of 1 bg/y biodiesel (by 2012), it is likely that a larger share of U.S. produced fuel will remain in this country.

Growth in the U.S. biodiesel industry in recent years has been very rapid. Figure 9 provides information about both biodiesel production and total plant capacity over the past several years. This illustrates that while production has grown significantly, capacity growth has been even more dramatic. Consequently, capacity utilization is declining. Utilization was 42% of capacity in 2006, but is estimated to be below 25% in 2008.⁽²⁵⁾ Similar to the European situation, this underutilization is a serious problem for the U.S. industry, caused by limited availability and high costs of feedstocks.



Figure 9. U.S. Biodiesel Capacity and Production

As shown in Fig. 10, the dominant biodiesel feedstock in the U.S. (and Brazil) is soybean oil, although a number of other materials are also used. This is in contrast to the European countries, where rapeseed oil dominates. Waste cooking oil, canola oil, animal fats, and other triglycerides are finding increased usage in the U.S. as soybean oil supplies are becoming more limited and costly.



Figure 10. Biodiesel Feedstocks by Country - 2007

In the U.S., approximately 70 million acres of U.S. farmland are used for soybean cultivation. The fraction of the soybean crop used for biodiesel production is small, but increasing. Accurate

determinations are difficult to make, since only a relatively small fraction of the soybean is used for fuel production, while most is used for animal feed and other purposes. However, it is estimated that the fraction of the total soybean crop devoted to biodiesel was 6% in 2005-2006, 8% in 2006-2007, and could reach 20% in 2008.⁽²⁵⁾ A recent DOE study has concluded that a 3 bg/y U.S. biodiesel industry would require 30 million acres of cropland to be used for seed oil production.⁽³⁵⁾ Achieving this level will also require substantial increases in seed oil yield per acre. Numerous R&D efforts are underway to genetically modify soybeans (and other crops) to enhance yields and improve fuel properties.^(36,37) In addition, improved agricultural production (fertilizer inputs, low tillage, and other) are leading towards higher yields.

To help put these figures into perspective, trends in total vegetable oil production over the past several years are shown in Figure 11. Fig. 11a shows U.S. production; Fig. 11b shows world-wide production. These data were obtained from the Economic Research Service of USDA.⁽³⁸⁾ Current soybean oil production in the U.S. has increased considerably over the past few years, and currently stands at approximately 3 bg/y, with about 0.5 bg/y of this being used for biodiesel production. This amount would need to double to 1 bg/y to satisfy the EISA biomass-based diesel requirement by 2012. Alternatively, greater use of other feedstocks, such as canola, could be employed to satisfy the EISA requirements.

As shown in Fig. 11b, equally rapid growth in vegetable oil production has occurred outside the U.S. Over the past 5 years, total world-wide vegetable oil production has increased at a rate of approximately 7% per annum. The largest global contributor is palm oil, followed by soybean, rapeseed, and sunflower seed.







World Vegetable Oils 2003/04-2007/08



Growth in total biodiesel capacity in the U.S. is being driven by the introduction of several very large production plants. For example, Imperium Renewable Corp. has opened a 100 mg/y plant in Grays Harbor, Washington; Green Hunter Energy has opened a 100 mg/y plant in Houston. Also, ConocoPhillips and Tyson Foods have announced plans to build the largest U.S. biodiesel plant, at 175 mg/y capacity. While the average U.S. plant size is still quite small at 12 mg/y, the trend is towards much larger plants. Figure 12 shows the extent of this growth trend in just one year, between 2006 and 2007. Fewer than 20 plants are responsible for 90% of the total biodiesel produced in the U.S.

In addition to biodiesel plant size increasing, the locations are migrating away from the traditional farm belt regions towards international port locations (Houston, Puget Sound, Boston, etc.) The same trend is occurring globally, with very large biodiesel plants existing (or being built) near Rotterdam, Singapore, and other major port locations.) These new locations provide access to a much wider range of potential feedstocks. Thus, the historically close connection between biodiesel and local agriculture is starting to weaken.



Figure 12. Growth in U.S. Biodiesel Plant Size

3.1.3 Other Countries

Numerous other countries are beginning to develop biofuels in general, and biodiesel in particular.⁽³⁹⁾ In most of these locations, the biodiesel industry is still very small and poorly documented. Three countries that have advanced quite far, and have definite plans for increased development, are Brazil, China, and India. These three are also highlighted in the Biodiesel 2020 Market Survey report, which provides some documented information about their biodiesel operations.⁽²⁵⁾

3.1.3.1 Brazil

At the end of 2007, Brazil had 42 biodiesel plants in operation, with a total production capacity of about 560 mg/y. Considerable growth is forecast in both the number of plants and actual production of biodiesel in Brazil, with the State oil company, Petrobras, playing a significant role in this development.

Currently, about 90% of Brazilian biodiesel is produced from soybean oil, with much smaller contributions from cottonseed, sunflower seed, castor seed, rapeseed, corn, palm, coconut, and other feedstocks.⁽²⁶⁾ Brazil is actively promoting the growth of agriculturally-derived feedstocks, and is opening up new (non-rainforest) areas for this.⁽⁴⁰⁾ Expansion of soybean cultivation is particularly preferred in the near term, due to its current high demand and favorable growing conditions. Brazil is likely to become a major exporter of both food and fuel from soybeans. Other biodiesel feedstocks that appear very promising for Brazil include castor, jatropha, palm, and cottonseed.

3.1.3.2 China

China is now the second largest energy consumer in the world (after the U.S.). Petroleum demand in China is growing very rapidly, at about 4% per annum, while production remains relatively stable near 3.5 mb/d. Currently, China imports about 40% of its petroleum, but this fraction is rising rapidly, and is expected to reach over 60% by 2020. These factors have caused China to begin aggressively promoting development of domestic biofuels.

China's biofuels industry is still in its infancy. Currently, there are approximately 35 biodiesel plants in operation, but all are quite small. Total biodiesel production is estimated to be 50-60 mg/y. In 2006, China announced very aggressive plans for growing biodiesel production to over 3 bg/y by 2010 and 5 bg/y by 2020. The main feedstocks identified to meet these goals are animal fats and waste vegetable oils by 2010, to be supplemented with new non-food crops (especially jatropha) by 2020.⁽⁴¹⁾ In view of concerns about food supply, China has now greatly reduced its projected volumes of biodiesel. The current feedstock focus is on waste vegetable oil and palm oil from Malaysia. For the longer term, China is pursuing the development of jatropha and other non-food sources.

At the present time, China has approximately 4 million hectares (10 million acres) of land area for growing oil-bearing trees, with an increasing fraction being devoted to jatropha. The first sizeable harvest of jatropha trees (also called "diesel trees" in China) is expected in 2008. By 2010, China anticipates having 13 million hectares (32 million acres) planted in jatropha – a size approximately equal to the landmass of England. Once fully productive, this could provide 2-4 bg/y of biodiesel.

3.1.3.3 India

India is currently the sixth largest energy consumer in the world. Similar to China, India is experiencing very rapid growth in demand for petroleum. Current petroleum consumption in India is approximately 40 bg/y, while diesel fuel consumption is about 15 bg/y. Diesel fuel accounts for about 80% of all transportation fuels in India. At present, India imports 72% of its petroleum, with this fraction increasing each year. Because of the growing gap between production and consumption, India is pursuing an

aggressive path towards biofuel development, as laid out in their "National Mission on Biodiesel."

Current commercial production of biodiesel in India is almost negligible.⁽⁴²⁾ Although accurate statistics are not available, it seems likely that current levels are close to 0.5 bg/y.⁽⁴³⁾ The Government of India has established a 5% biodiesel blend requirement beginning in 2010, which translates to a volume of about 1 bg/y. Achieving a 10% goal by 2020 would require about 3.5 bg/y of biodiesel. (The stated goal for 2020 is still 20%, but presently, this does not seem achievable.) The largest users of biodiesel include Indian Railways and other state-owned transport companies that have established experimental trial projects for biodiesel production.

Current feedstocks for biodiesel production in India are quite varied, including waste vegetable oil, animal fats, rubberseed oil, rice bran, karanja, pongamia, and especially jatropha.⁽⁴⁴⁾ Due to government policies and high edible oil prices, it is not feasible to produce biodiesel from vegetable oils in India. While still in its infancy, India intends to greatly expand its use of jatropha. To meet the 5% biodiesel goal by 2010 will require approximately 2.5 million hectares (6.2 million acres) of jatropha and karanja. Meeting the 20% goal by 2020 would require about 20 million hectares (49 million acres). The Government of India has identified sufficient space for such plantations, mostly involving land that is not used productively at present. Significant advantages of jatropha (and some other native plants) include its ability to grow on marginal land with modest requirements for water and fertilizer. In India (and elsewhere) developing a jatropha industry is also seen as a powerful driver for rural economic development.

3.2 Algal Feedstocks

Many varieties of microalgae are known to produce large quantities of lipids, containing triglyceride oils, which are potential feedstocks for biodistillate fuels. Of all photosynthetic organisms, microalgae are the most productive users of CO_2 , and can fix larger amounts of CO_2 per land area than other plants (see Table III).⁽⁴⁵⁾ Some of the most commonly cited factors for favoring algae as a biofuel feedstock include the following:

- Rapid growth
- High oil content
- Tolerance for poor quality water
- Use of relatively little land space
- Use of non-productive land
- Mitigation of fossil CO₂ emissions
- Use of wastewater treatment effluents for nutrients
- Production of valuable co-products

Various investigations have been conducted to determine suitable algal strains for maximum growth and oil production under specific conditions. The most comprehensive investigation of algae as a potential fuel feedstock was undertaken by the National Renewable Energy Laboratory (NREL), who maintained an active Aquatic Species Program (ASP) from 1978 to 1996. The ASP final closeout report was issued in 1998, and remains an excellent source of information about growth conditions and productivities of various algal strains.⁽⁴⁶⁾

Due to numerous technical and economic factors, the ASP was discontinued. Now, however, DOE and NREL have renewed interest in promoting algae as a commercial energy source. In fact, DOE recently sponsored an "Algal Fuels Roadmapping" meeting, and plans to issue a roadmap document in mid-2009. ⁽⁴⁷⁾ Reasons cited for this renewed interest include the following:

- High costs of petroleum and other energy sources
- Increased emphasis on energy security
- Concern about CO₂ and climate change
- Advances in biotechnology and photobioreactor designs
- Petroleum refiners' interest in processing lipids

Major barriers to commercial scale implementation of algal systems include numerous technical challenges (maintaining healthy algal growth, avoiding invasive native algae, temperature control, effective light dispersion, reliable harvesting methods, effective extraction of oils, etc.) as well as economics.^(48,49,50) The standard operations currently in use for microalgae biomass production (mainly for producing high-value food supplements) involve open "raceway ponds," with sparging of CO₂-containing gases into the ponds. There is also considerable interest in closed, photobioreactor designs, which help maintain purity of the desired algal strains being used and offer better control of operating controls (nutrient levels, irradiation, flow rates, etc.), but with much higher capital and operating costs.⁽³¹⁾ The economics of algal fuel systems may be improved by combining them with waste water treatment operations that can provide much of the nutrients needed for algal growth.

In addition to lipids, many algal strains produce large amounts of carbohydrates and protein. The proteins are useful as food/feed supplements, while the carbohydrates are potential feedstocks for fuels via biochemical and themochemical processing approaches.

Current interest in developing algae-to-biofuels systems and technologies is extremely high. This is evident from the extensive list of companies and organizations shown in Appendix III who are presently working in this area. Despite this tremendous interest, there currently are no functioning, commercial-scale operations producing biodistillate fuels from algae. However, this situation may change soon, as substantial investments by major technology developers and fuel producers are being made. As one example, the Defense Advanced Research Projects Agency (DARPA) is now supporting development and demonstration projects to produce military jet fuel (JP-8) from algae.⁽⁵¹⁾

3.3 Other Triglyceride Feedstocks

It has been reported that over 350 oil-bearing crops exist in the world.⁽³²⁾ The literature is replete with reports of biodiesel produced from diverse feedstocks around the world. Many of these reports describe use of seed oils from rather obscure, local plants. Table IV provides a listing of many (but certainly not all) such reports.

Perhaps the greatest interest in seed oil feedstocks for biodiesel is in India. As described above, India has very aggressive plans for large-scale commercialization of Jatropha plantations. Other India feedstocks of significant interest include pongaia, ^(52,53,54,55) karanja, ^(56,57,58) soapnut⁽⁵⁹⁾, bran^(60,61), and rubber seed. ⁽⁶²⁾ Other feedstocks of interest in South America (especially Brazil and Argentina) include tucum, ⁽⁶³⁾ babassu, ^(64,65) and castor oil. ⁽⁶⁶⁾ Other potential European feedstocks of interest include cottonseed, ⁽⁶⁷⁾ carinata^(68,69,70) and cynara. ^(71,72,73) Potential seed oil feedstocks that have been investigated in the U.S. include milkweed, ⁽⁷⁴⁾ mustard, ⁽⁷⁵⁾ tobacco seed, ⁽⁷⁶⁾ and camelina. ^(77,78)

NORTH AMERICA		
Reported Feedstock	Edible	
Algae	No*	
Beech	No	
Camelina	Yes	
Corn Oil	Yes	
Cottonseed Oil	Yes	
Jatropha	No	
Lesquerella	No	
Linseed	Yes	
Rape Seed	Yes	
Safflower	Yes	
Soapnut Oil	No	
Soybean	Yes	
Spruce	No	
Sunflower Oil	Yes	
Walnut	Yes	

EUROPE		
Reported Feedstock	Edible	
Algae	No*	
Beech	No	
Camelina	Yes	
Cottonseed Oil	Yes	
Hazelnut	Yes	
Jatropha	No	
Linseed	Yes	
Poppy Seed	Yes	
Rape Seed	Yes	
Safflower	Yes	
Soapnut Oil	No	
Spring Mustard	Yes	
Spruce	No	
Walnut	Yes	

SOUTH/CENTRAL AMERICA		
Reported Feedstock	Edible	
Algae	No*	
Andiroba	Yes	
Babassu	Yes	
Castor Oil	No	
Coconut Oil Yes		
Cottonseed Oil	Yes	
Cumaru		
Jatropha	No	
Lesquerella	No	
Linseed	Yes	
Palm Oil	Yes	
Peanut	Yes	
Rubber Seed Oil	No	
Safflower	Yes	
Soapnut Oil	No	
Tucum oil	Yes	

Table IV. Vegetable Oils used for Biodiesel Production

AFRICA			
Reported Feedstock	Edible		
Algae	No*		
Castor Oil	No		
Cottonseed Oil Yes			
Crambe No			
Cynara			
Jatropha	No		
Linseed	Yes		
Olive	Yes		
Palm Oil	Yes		
Polanga	No		
Safflower	Yes		
Sesame	Yes		
Soapnut Oil	No		

ASIA			
Reported Feedstock	Edible		
Ailanthus	No		
Algae	No*		
Camelina	Yes		
Castor Oil	No		
Cottonseed Oil	Yes		
Hazelnut	Yes		
Jatropha	No		
Karanja	No		
Linseed	Yes		
Mahua	Yes		
Neem			
Olive	Yes		
Palm Oil	Yes		
Polanga	No		
Pongamia	No		
Poppy Seed	Yes		
Rice Bran	Yes		
Safflower	Yes		
Sesame	Yes		
Soapnut Oil	No		
Spring Mustard	Yes		
Spruce	No		
Vann	Yes		
Walnut	Yes		

* some algae, or portions of algae, are edible

Besides seed oils, a wide variety of animal fats have been used as biodiesel feedstocks – especially from beef, hogs, sheep, and poultry. Other significant feedstocks are fats and oils recovered from restaurant cooking activities. These are commonly referred to as yellow grease (used cooking oil) and brown grease (recovered from grease traps). In the U.S., total annual production of animal fats and used vegetable oils is estimated at 1.6 bg/y.⁽³²⁾ Other, minor non-food related feedstocks include tall oil from paper/pulp manufacturing,⁽⁷⁹⁾ fleshing wastes from leather production,⁽⁸⁰⁾ sewage sludge,⁽⁸¹⁾ and waste from fish oil.⁽⁸²⁾

3.4 Lignocellulosic Feedstocks

If plant-derived biofuels are to play a significant role in satisfying transportation fuel demands in the U.S. and elsewhere, it is necessary to consider feedstocks that are more diverse and abundant than triglycerides – such as lignocellulosic biomass. The term "lignocellulose" is used when referring to a combination of the three primary polymers that make up plant cell wall: cellulose, hemicellulose, and lignin. Depending upon plant species and cell type, the dry weight of a cell wall typically contains about 35-50% cellulose, 20-35% hemicellulose, and 10-25% lignin.⁽⁸³⁾

Lignocellulosic biomass resources are commonly categorized as deriving from forest resources or agricultural resources. More detailed examples of subcategories within these resources are shown below in Table V.

	Forest Resources	Agricultural Resources
Primary	Logging residuesForest fuel treatmentFuel wood	 Crop residues Grain Perennial grasses Woody crops
Secondary	Mill residuesPulping liquorsWood processing residues	Animal manuresFood/feed processing residues
Tertiary	 Construction debris Demolition debris Urban tree trimmings Packaging waste 	Municipal solid waste (MSW)Landfill gases

Table V. Biomass Resource Classification

Recently, the USDA and DOE collaborated on a study to assess the biomass resource base within the U.S., both currently and in the future.⁽⁸⁴⁾ A particular objective was to determine whether the land resources of the U.S. are capable of producing a supply of biomass sufficient to displace 30% or more of the country's present petroleum consumption. Achieving this goal was estimated to require a continuous supply of 1 billion dry tons per year (bdt/y) of biomass feedstock.

This so-called "Billion Ton Study" considered several modeling scenarios which included numerous sets of assumptions. In the case of forest biomass resources, the study concluded that today's level of 142 mdt/y could be increased to 368 mdt/y, mainly by: (1) greater use of urban waste residues, (2) use of forest thinnings removed by fire prevention treatments, and (3) greater use of logging residues. These projections are illustrated below in Fig. 13.



Figure 13. U.S. Forest Biomass Resources – Current and Potential Future Amounts (Taken from Reference No. 1)

Even greater potential biomass amounts are available from agricultural resources. In this area, the Billion Ton Study developed various scenarios having different assumptions regarding crop yields, land use changes, harvesting efficiency, tillage practices, and introduction of perennial crops for biomass. The main results from these scenarios are presented graphically in Fig. 14.



Figure 14. U.S. Agricultural Biomass Resources – Current and Potential Future Amounts (taken from Reference No. 1)

In this figure, Scenario 1 represents the current U.S. agricultural situation, where the total amount of biomass available for energy conversion is estimated to be 194 mdt/y (although most of this is not used today). Scenario 2 assumes continued use of conventional agricultural lands and crops, but with increased crop yields representing what could reasonably be expected in 2020 (424 mdt/y) and 2040 (597 mdt/y). No land use changes are assumed in Scenario 2.

Scenario 3 assumes introduction of new, perennial crops (grasses and trees) grown for energy uses, as well as some land use changes. As in Scenario 2, moderate and high yield increases are used to represent

biomass amounts that could be expected in 2020 (581 mdt/y) and 2040 (998 mdt/y). The principal land use changes in Scenario 3 are modest reductions in the amounts of active cropland and idle land, to allow for introduction of perennial crops. It is important to note, however, that in this Billion Ton Study, no changes in total acreage were assumed. Further details of the land allocation assumptions used in this study are given below in Table VI.

	Scenario 1 (current allocation)	Scenario 2 (moderate and high yield increases)	Scenario 3 (moderate yield increase)	Scenario 3 (high yield increase)
Active cropland	344	344	339	319
Idle land	37	37	27	27
Pasture	68	68	43	43
Perennial crop	0	0	40	60
Total	449	449	449	449

Table VI. U.S. Land Allocations used in USDA/DOE Billion Ton Study, million acres

Numerous other assessments of lignocellulosic feedstock availability, logistics, economics, and growth potential have been conducted in recent years. On a national level, these efforts have been driven mainly by DOE and USDA. Relevant documents to consult include the Biomass Multi-Year Program Plan,⁽⁸⁵⁾ the Roadmap for Agricultural Biomass Feedstock Supply,⁽⁸⁶⁾ the Genomics: GTL Roadmap,⁽⁸⁷⁾ and the Roadmap for Bioenergy and Biobased Products in the U.S.⁽⁸⁸⁾

In addition, several states have been actively investigating their biomass resources as potential feedstocks for fuels. Of particular note is California, where the California Energy Commission (CEC) recently conducted a Biomass Resource Assessment for the State,⁽⁸⁹⁾ and issued a Preliminary Roadmap for the Development of Biomass in California.⁽⁹⁰⁾

3.5 Near-Term Biodiesel Market Trends

The global biodiesel/renewable diesel industries are rapidly evolving – driven by both regulatory requirements and business economics. In this section, we briefly mention a few of the most significant current market trends, and those expected in the near future (approximate 5-year time horizon). This relatively short time period precludes significant introduction of lignocellulosic feedstocks for production of plant-derived biofuels. Thus, our discussion here focuses on the traditional triglyceride feedstocks. Five main points are summarized below:

- <u>Enormous over-capacity at present</u>: Current biodiesel production in the U.S. and Europe is well below 40% of capacity. Plant capacity has grown dramatically over the past few years, while feedstock supplies have not. This has resulted in high feedstock costs, increased interest in feedstock diversity, shut-down of some plants, and uncertain near-term economic outlook for many other existing plants.
- <u>Scramble for currently available feedstocks</u>: Although soybeans (U.S.) and rapeseed (Europe) continue to dominate, many more feedstocks are being investigated, and are likely to find increased commercial use in the near future. Waste cooking oils and animal fats while always used to some extent are likely to become more important globally. While relatively abundant on a global scale, increasing amounts of palm oil are not expected to be diverted to biodistillate production, due to competing demands as a food stock.

- <u>Search for non-food feedstocks</u>: Concerns about food vs. fuel are driving many countries to search for non-food biofuel feedstocks. Two receiving the greatest attention at present are jatropha and algae. Several countries (especially India, China, and some African countries) have aggressive plans to develop millions of hectares in jatropha plantations within the next 5-10 years. Commercial scale algae production will likely lag behind jatropha by a few years. However, interest and investment in algae-to-fuels processes are growing, and we expect that some commercial operations will be realized within 5-10 years.
- <u>Biodiesel is becoming mainstream, big business</u>: While most biodiesel plants in operation today are very small (<25 mg/y) the recent trend is clearly towards larger and more flexible operations. Large plants are generally more sophisticated, allowing for wider diversity of feedstocks, greater quality control, and economics of scale. The location of large, new plants is being dictated more by access to international shipping of feedstocks than by proximity to locally-grown agricultural feedstocks. This trend towards larger, more complex biodiesel plants is illustrated in Fig. 15.
- <u>Involvement by Major Energy Companies</u>: In recent years, large international oil companies have become active participants is the biodiesel/renewable diesel industries. Significant operations are underway (or announced) by British Petroleum, Chevron, Marathon, ConocoPhillips, and Shell. The distinctions between petroleum diesel and biomass-based diesel are likely to become blurred in the future, as triglyceride feedstocks are increasingly used in conventional refinery processes to produce renewable diesel.



Figure 15. Trend towards Large Commercial-Scale Biodiesel Plants

4. Biodistillate Production Technologies

There is a long record of using straight vegetable oil (SVO) as fuel for compression ignition engines, going back to Rudolph Diesel (1853-1913) himself. The literature contains many references to the early use of SVO as a "diesel fuel," and cites numerous advantages of such usage.^(91,92,93,94) Among these advantages are the following:

- SVO is a high energy, easily transported liquid fuel (about 90% the heat content of petroleum diesel)
- Vegetable oils are ubiquitous around the world, making local fuel supply possible
- Some vegetable oils crops can be grown on marginal lands, promoting rural economic development
- Refining SVO involves relatively simple (and inexpensive) processes
- SVO has low sulfur and aromatic levels
- SVO is renewable and biodegradable

On the other hand, SVO has some major disadvantages, which make it unacceptable as a diesel fuel in nearly all situations. Vegetable oils are composed of 90-98% triacylglycerides, commonly referred to as triglycerides, along with small amounts of mono- and di-glycerides, free fatty acids, phospholipids, and other trace constituents.⁽⁹³⁾ The molecular weight (MW) range for most triglycerides is 700-950, much higher than typical petroleum diesel which has MW range of 200-350. This results in triglycerides having much higher viscosities than petroleum diesel. Typical viscosities of vegetable oils are 35-60 cSt at 40°C, compared to about 2-3 cSt for petroleum diesel. Figure 16, taken from a DOE Fact Sheet, compares the viscosity of sunflower oil and conventional diesel fuel over a range of temperatures.⁽⁹⁵⁾

The high viscosity of SVO is a major cause of poor fuel atomization that can lead to operational problems of poor combustion, injector coking, deposit formation, and others.^(96,97) Several approaches have been taken to overcome the problem of SVO's high viscosity, and allow vegetable oil-based materials to be used in diesel engines. In general, these approaches can be classified into four groups:

- 1. Dilution with conventional diesel fuel
- 2. Microemulsification
- 3. Transesterification



Figure 16. Viscosity of Sunflower Oil and Petroleum Diesel

4. Thermal conversion

Of these four approaches, the first two do not change the chemical structure of the triglyceride molecules, while the second two do. Simple dilution of vegetable oils with petroleum diesel has been widely used, but with mixed success.^(94,98,99) Lower blend levels of SVO (<20%) are generally more acceptable than high blend levels, but long term concerns still remain due to high viscosity, free fatty acid content, storage stability, lube oil thickening, and other problems.^(96,100)

Microemulsions of SVO with alcohols have also been used to reduce viscosity.^(98,99) Often, a surfactant is necessary to maintain stability of the microemulsion. Many different formulations of SVOs, alcohols, and surfactants have been investigated – with somewhat mixed results. Due to difficulties in preparing these microemulsions, maintaining their stability in real-world applications, and gaining consumer acceptance, the use of such fuels has not been widespread.

By far the most common method for overcoming the viscosity problem of SVO is transesterification, though recently there has been growing interest in hydroprocessing and other thermal methods of treating SVO. The remainder of this section deals with these processes.

4.1 Transesterification

Transesterification is the chemical process by which triglycerides are reacted with alcohols to produce fatty acid alkyl esters and glycerol. These fatty acid esters [usually fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE)] are commonly known as biodiesel. In the past few years, several excellent reviews on the topic of biodiesel manufacturing have appeared in the literature.^(101,102,103,94) Given below is a discussion of some important aspects of biodiesel production.

4.1.1 Biodiesel Production Chemistry

The basic chemical reactions involved in the production of biodiesel are shown below in Fig. 17. One mole of a triglyceride is reacted with three moles of alcohol (usually methanol) in the presence of an alkaline catalyst to produce three moles of biodiesel and one mole of glycerol. For simplicity, the chemical structures in Fig. 17 only show fully saturated molecules. In reality, triglycerides in fats and oils have varying degrees of unsaturation (carbon-carbon double bonds) which is retained in the biodiesel product. Also, the carbon chain length in triglycerides typically varies from C_{12} to C_{20} . (More discussion of composition is provided later in this report.)





For reasons of cost and ease of reaction, the most common alcohol used in the transesterification process is methanol, leading to the production of FAME, as shown in Fig. 17. However, there are also numerous reports of using ethanol in place of methanol, leading to formation of FAEE.^(104,105,106) The use of ethanol offers the possibility of total renewable feedstocks, whereas methanol is generally produced from fossil sources (natural gas). Additionally, some locations, such as Brazil, have an abundance of locally-produced, low-cost ethanol.

4.1.2 Commercial Biodiesel Reaction Conditions

A simplified process flow diagram for producing biodiesel from vegetable oils is shown below in Fig. 18. This depicts a common, small operation utilizing a batch process. Most large biodiesel plants use continuous processes, which generally include multiple reactors in series, with settling vessels located between the reactors. Several thorough descriptions of common biodiesel production technology are available in the literature.^(103,107)



Figure 18. Process Flow Diagram for Typical, Batch-Mode Biodiesel Production

Considerable work has been conducted to determine optimum reaction conditions for producing biodiesel. To some degree, different conditions are required for each triglyceride feedstock. For a given feedstock, numerous factors have been found to have significant impacts on process efficiency and purity of final product.^(94,103,108) Several of the most important factors are discussed below in more detail:

4.1.2.1 Ratio of Alcohol to Triglyceride

According to the stoichiometry shown in Fig. 17, the theoretical molar ratio of alcohol to triglyceride is 3/1. However, in most commercial operations, a much higher ratio of alcohol/triglyceride is used – typically around 6/1. The main reason for using excess alcohol is to drive the transesterification reaction to completion. As shown in Fig. 19, transesterification of triglycerides actually proceeds through a

stepwise process involving intermediate production of a diglyceride, and a monoglyceride, before the final glycerol product is released. At each of these three steps, a molecule of FAME is produced. To ensure acceptable biodiesel product quality (discussed further in the next section) it is critical for these reactions to proceed to completion, so that concentrations of the intermediate diglycerides and monoglycerides in the finished fuel are kept very low. Other reasons for using excess



Figure 19. Step-Wise Process of Biodiesel Formation

alcohol are to provide some solvency for the reactants and to assist in separation of glycerol from the product FAME. However, use of an excessive amount of alcohol is avoided, since considerable energy is required to distill the unreacted alcohol from the final FAME product.

4.1.2.2 Type of Alcohol

Although nearly any alcohol could be used in the transesterification process, in most cases, methanol is the alcohol of choice. This is not only an economic decision; several technical factors are also involved. First, the transesterification reaction rate is significantly faster with methanol than with higher alcohols.^(109,110,111) Also, higher alcohols are better solvents for glycerol and other impurities, making it more difficult to separate these materials from the desired biodiesel product. Finally, higher alcohols (especially ethanol) are more difficult (and more expensive) to dry. As discussed below, the presence of water is very problematic in biodiesel production processes.

4.1.2.3 Purity of Triglyceride Feedstock

The amount and type of impurities present in triglyceride feedstocks are critical factors dictating optimum conditions for transesterification. Perhaps most important is the free fatty acid (FFA) content of the starting feedstock. As shown in the reactions of Fig. 20, FFA will react with the alkali catalyst to produce salts. This is very detrimental. Not only does salt formation "waste" the energy-rich FFA by eliminating its contribution to the final fuel, it also causes severe foaming and separation problems. To overcome this, it is generally recommended that feedstocks containing over 1% FFA first undergo a preliminary acid-catalyzed esterification process.⁽¹⁰¹⁾ This pretreatment produces FAME and water, while the triglyceride remains largely unreacted. Following neutralization and drying, the conventional alkali-catalyzed transesterification reaction is then conducted to complete formation of the biodiesel. This 2-step approach appears to be used quite widely.^(112,113,114) While this 2-step process for biodiesel production adds complexity and equipment, it can be financially advantageous since it allows for use of less expensive triglyceride feedstocks, such as waste cooking oils and soapstocks.^(101,112,115,116,117,118)



Figure 20. Other Important Reactions in Biodiesel Production Processes (For simplicity, only saturated fatty acid structures are shown)

4.1.2.4 Amount and Type of Catalyst

There has been much research to investigate the use of different catalysts for biodiesel production, but commercially, only two general types are used in significant amounts: (1) hydroxides (NaOH and KOH) and (2) methoxides (NaOMe and KOMe). For reasons of cost and availability, NaOH is often the catalyst of choice.^(101,110) However, sodium methoxide (NaOMe, also called sodium methylate), is becoming increasingly common, despite higher cost, due to its ease of storage and handling, and the improvements

in process efficiency that result.^(108,119) In particular, use of sodium methoxide avoids the problems associated with water formation that occur when hydroxide catalysts are used with alcohols (e.g. NaOH + MeOH \rightarrow NaOMe + H₂O). The presence of water promotes hydrolysis of triglycerides, producing FFA with the attendant problems of soap formation (see Fig. 20 above). An additional problem with KOH (and to a lesser extent with NaOH) is that when purchased as a "pure" solid, it still contains appreciable amounts of water.

4.1.2.5 Reaction Time and Temperature

Reaction time and temperature are generally optimized for each situation. For commercial, alkalicatalyzed, batch-mode transesterification with methanol, typical reaction temperatures are in the range of 50-60°C (slightly below the boiling point of methanol), with a reaction time of about 1-hour.^(107,102,103) With use of ethanol in place of methanol, slightly higher reaction temperatures are used.

Somewhat surprisingly, despite many years of experimentation, and the existence of a rich literature database, considerable efforts continue today in defining optimum process conditions for producing biodiesel via transesterification of triglycerides. Evidence of this is the appearance of several very recent publications which describe optimization of reaction conditions for transesterification of rapeseed oil,⁽¹²⁰⁾ safflower oil,⁽¹²¹⁾ linseed oil,⁽¹²²⁾ and rice bran oil.⁽¹²³⁾

4.1.3 Modifications to Typical Transesterification Conditions

The sections above were meant to present typical commercial biodiesel processes, and discuss the most important factors affecting biodiesel production. However, there are several other process issues worthy of mention, although most of them remain in the R&D arena rather than in commercial applications.

4.1.3.1 Co-Solvents

As already mentioned, triglycerides are very sparingly soluble in methanol, and only slightly more soluble in ethanol. This limits the transesterification reaction rate, and is one reason why a large excess of alcohol is generally used. To help overcome this problem, several researchers have investigated the use of cosolvents that increase the interaction between the triglyceride and alcohol. Tetrahydrofuran (THF) is one co-solvent that has been widely used.⁽¹²⁴⁾ More recently, dimethylether (DME) has been reported as an attractive co-solvent.⁽¹²⁵⁾ DME is particularly advantageous since it can easily be flashed off and recycled at the end of the reaction. Similarly, CO₂ has been reported as a useful co-solvent, though this requires use of pressure reactor vessels.⁽¹²⁶⁾

4.1.3.2 Heterogeneous Catalysts

While most commercial biodiesel production involves use of soluble, homogeneous catalysts such as hydroxides or methoxides, there has been tremendous R&D interest in development of heterogeneous catalysts.^(124,127) Several dozen of the bibliography entries shown in Appendix II as dealing with biodistillate fuel production technology are focused on this topic of heterogeneous catalysis. In most cases, these catalysts consist of metal oxides^(128,129,130,131) ion exchange resins,^(132,110) or other materials immobilized on solid supports.^(133,134,135,136)

There are several clear advantages to use of heterogeneous catalysts. Perhaps most important, avoiding soluble hydroxide catalysts eliminates the problems associated with saponification and water contamination. Consequently, there is no ester loss due to soap formation, and the by-product, glycerol, is obtained in much higher purity. Additionally, biodiesel purification is considerably easier, since there is no soluble catalyst to remove. As a downside, somewhat higher reaction temperatures are required, since the heterogeneous catalysts are generally less reactive.

The only commercial application of a heterogeneous catalytic process for biodiesel production that we are aware of was developed by the French Petroleum Institute, and is being used at a plant in France.⁽¹⁰⁹⁾ Another recent publication reports use of a metal oxide fixed bed reactor for producing biodistillate fuel.⁽¹³⁰⁾ Under the high temperature and high pressure conditions of this so-called "Mcgyan Process," methanol exists in a supercritical state, and the glycerol product is dehydrated to form light gases (CO, CO_2 , CH₄, and dimethyl ether).

A particular topic of heterogeneous catalysis receiving considerable current interest involves enzymatic materials, such as lipases, immobilized on solid supports.^(105,106,112,137,138,139,140) As with the heterogeneous catalysts mentioned above, enzymatic catalysts provide for cleaner separation of high quality biodiesel, and production of high purity glycerol. Additionally, it is reported that use of enzymatic catalysts allows for milder reaction conditions and better performance for ethanol compared to methanol.⁽¹⁰⁶⁾ However, enzymatic catalysts entail high costs and are still regarded as experimental. We are not aware of any commercial biodiesel production process that utilizes enzymatic catalysts today.

4.1.3.3 Supercritical Reaction Conditions

In recent years, there have been several reports of using supercritical conditions to enhance the transesterification reactions of triglycerides with methanol.^(43,93,141,142,143,144) Methanol becomes a supercritical fluid at temperatures above 240°C and pressures above 8.1 MPa. Under these conditions, methanol and triglycerides become miscible, greatly accelerating the transesterification reaction, without the presence of added catalyst. Other advantages of supercritical conditions are elimination of salt formation, production of high purity glycerol, reaction of both free fatty acids and triglycerides, tolerance of water contamination, and easy cleanup of the desired biodiesel product. A recent publication reports greater oxidative stability of biodiesel produced via supercritical methods compared to the conventional alkali-catalyzed process.⁽¹⁴⁵⁾

However, there are disadvantages to supercritical processes as well. Generally, a very large excess of methanol is used (40/1 ratio of methanol/triglyceride) requiring considerable energy to distill and recover the unreacted alcohol.^(146,147) Also, to achieve high reaction rates requires quite high temperatures (300-350°C) and high pressures (15-20 MPa). This entails higher capital cost in equipment that can tolerate these temperature and pressure demands.

There is evidence that at temperatures above 300°C, cis-to-trans isomerization of the olefinic structures in FAME can occur, leading to a degradation in cold flow properties.⁽¹⁴⁸⁾ One suggested approach to reducing the severity of supercritical reaction conditions is to use two or more reactors in series, with glycerol removal between the reactors. In this way, temperatures as low as 275°C, pressures as low as 10 MPa, and methanol/triglyceride ratios as low as 10/1 can be used.⁽¹⁴⁷⁾

One additional supercritical process for producing biodiesel looks promising, but has not yet been widely studied, involves use of ethanol in place of methanol. The conditions required to produce supercritical ethanol are slightly milder than for methanol – about the same temperature, but lower pressure (6.4 MPa vs. 8.1 MPa).^(149,150) This may be a fruitful area for further research.

4.1.3.4 Ultrasonic and Microwave Conditions

There are a few reports in the literature of using low-frequency ultrasonication (24-40 kHz) to enhance the transesterification reaction of triglycerides with short chain alcohols.^(151,152,153,154,155,156) Ultrasonication has the effect of emulsifying immiscible liquids, thus improving the contact between the reactants and enhancing the reaction rate. Although this may result in a shorter reaction time, the process still requires alkali catalysts, with attendant problems due to salt formation and clean-up of the produced biodiesel.

Another reported enhancement in the transesterification of triglycerides with methanol involves use of microwave irradiation, in either a batch or continuous process.^(157,158) The benefit imparted by microwave irradiation is rapid heating of the reaction mixture, resulting in faster reaction rates. One group of researchers has reported that use of microwaves is a more energy efficient process than use of conventional heating approaches.⁽¹⁵⁹⁾ Another group has reported that use of microwaves can increase the reaction temperature to supercritical conditions, in which case no additional catalyst is necessary.⁽¹⁶⁰⁾ Another recent publication reports the use of radio frequency (RF) heating to enhance transesterification.⁽¹⁶¹⁾ To our knowledge, there is no biodiesel production plant in commercial operation today that uses ultrasonication, microwave, or RF irradiation to enhance the transesterification process.

4.1.4 Glycerol Considerations

As already discussed, production of glycerol by-product during the transesterification of triglycerides to produce biodiesel can lead to numerous problems. While high purity glycerol has many commercial outlets, ⁽¹⁶²⁾ the increasing production of biodiesel has led to a surplus of low quality glycerol, which requires extensive treatment to increase its value.⁽¹⁶³⁾ In rough terms, 1 lb. of glycerol is produced for every 10 lbs of biodiesel. The purity of glycerol at a typical, small biodiesel production plant is only 80-85%, even after water washing and further clean-up.^(101,109) Further purification of glycerol produced at small biodiesel production plants usually involves distillation at an off-site glycerol refinery. In contrast, large biodiesel production plants typically refine glycerol on-site.

Besides problems with purifying the glycerol by-product, the presence of glycerol as an impurity in biodiesel creates fuel quality problems and off-spec product. Water washing is typically employed to remove glycerol from biodiesel, but several washes – with intermediate separation steps – are required. In one published study, it was determined that 5-7 washes were required to give acceptable quality product.⁽¹⁶⁴⁾ Clearly, any process that avoids glycerol formation offers an advantage in this area.

Developing alternative, higher-value uses of glycerol has been identified by NREL as an important R&D area,⁽¹⁶⁵⁾ as this would improve the overall economics of biodiesel production. Currently, low-grade glycerol is used as a boiler fuel, where it can be cost competitive with natural gas.⁽¹⁶⁶⁾ With modest upgrading, glycerol can be used as an animal feed. Numerous approaches are also being investigated to use glycerol as a feedstock for the production of higher-value chemicals, including 1,3-propanediol,^(81,167) epichlorohydrin,⁽¹⁶⁸⁾ propylene glycol,^(169,170) and numerous other 3-carbon molecules.⁽¹⁶⁶⁾ One recent report describes use of glycerol as feedstock for a steam reforming process to produce hydrogen.⁽¹⁷¹⁾

One particularly interesting means of reducing glycerol involves transesterification of triglycerides with methanol in the presence of dimethylcarbonate (DMC). Under certain conditions, DMC chemically reacts with triglycerides to produce fatty acid glycerol carbonate (FAGC) along with conventional FAME.⁽¹⁷²⁾ (The chemical reaction is shown below in Fig. 21). By this means, the glycerol moiety is converted into a biofuel so that it does not need to be removed from the desired product.



Figure 21. Reaction of Triglycerides with Dimethylcarbonate

Another example of converting glycerol into a diesel fuel component was recently reported by the French Institute of Petroleum.⁽¹⁷³⁾ In this case glycerol was reacted with isobutylene to produce glycerol-t-butyl ether (GTBE), which was used as a diesel fuel blendstock. Finally, a group of Spanish researchers has investigated the reaction of glycerol with acetic acid to produce mono-, di-, and tri-acetylglycerol,⁽¹⁷⁴⁾ (MAG, DAG, and TAG, respectively). These products are reported to be beneficial as octane improvers for gasoline and low-temperature flow improvers for diesel fuel. The chemical reactions for this process are shown below in Fig. 22.



Figure 22. Reaction of Glycerol with Acetic Acid

4.2 Catalytic Hydroprocessing

In recent years, several academic and industrial organizations have investigated the conversion of triglyceride feedstocks into biodistillate products via catalytic hydroprocessing. One of the first commercial processes was reported in 2005, by Neste Oil Corporation.^(175,176) The product, called NExBTL, is a paraffinic hydrocarbon material (no aromatics, sulfur, oxygen, or nitrogen) suitable for blending into conventional diesel fuel. At about the same time, UOP in conjunction with Eni, reported a similar process called Ecofining[™].^(177,178)

The Neste Oil process involves a separate fuel processing unit that is integrated within a petroleum refinery.^(176,179) A variety of vegetable oils and animal fats can be used as feedstocks. The preferred hydroprocessing operating conditions are proprietary. Besides the hydroprocessing unit itself, the entire Neste Oil renewable diesel process includes pre-treatment of the feedstocks and clean-up of the final product. The hydrotreated vegetable oil (HVO) product is called "NExBTL" because it is regarded as a Next Generation biomass-to-liquids (BTL) fuel. Neste Oil indicates that the product composition is similar to that produced from other gas-to-liquid (GTL) or BTL processes.

UOP has investigated the production of renewable diesel by hydroprocessing of vegetable oils both as a stand-alone unit and by co-processing with petroleum feedstocks in a conventional diesel hydrotreater.⁽¹⁷⁷⁾ While acceptable quality renewable diesel can be produced by either approach, stand-alone operation is preferred.⁽¹⁸⁰⁾ Several reasons for this preference are as follows:

- High total acid numbers (TAN) of some triglyceride feedstocks requires metallurgical upgrades to typical ULSD hydrotreaters.
- Pre-processing equipment is often necessary to remove contaminants from feedstocks before feeding triglycerides into mid-distillate hydrotreaters.

- Typical operation of ULSD hydrotreaters favors hydrodeoxygenation reactions (loss of water) of triglycerides, producing water that can adversely affect catalyst performance.
- Stand-alone units allow for optimized selection of catalyst type and operating conditions, which can produce a renewable diesel with improved low temperature operability.

In contrast to the Neste Oil and UOP/Eni Ecofining[™] processes, a process recently developed by ConocoPhillips involves co-feeding triglycerides with petroleum feedstocks for hydroprocessing in a conventional diesel hydrotreater unit used for desulfurization.⁽¹⁸¹⁾ While detailed processing conditions are proprietary, typical hydrodesulfurization (HDS) conditions are said to be used. Other companies reported to be developing commercial hydroprocessing of triglyceride feedstocks include Petrobras, BP, and Syntroleum.⁽¹⁸²⁾

In all of these hydroprocessing cases several reactions occur, including hydrogenation of the olefinic groups within the triglyceride, decarbonylation (loss of CO), decarboxylation (loss of CO_2) and hydrodeoxygenation (loss of H_2O).^(183,184) These reactions are depicted below in Fig. 23. In these hydroprocessing reactions, most of the glycerol component in the original triglyceride is converted to propane, while most of the carboxyl carbons are converted to CO or CO₂. (The ratio of these products varies with the type of catalyst and operating conditions being used.) Since triglyceride compositions are dominated by even-numbered fatty acid components, removal of the carboxyl group results in biodistillates consisting mainly of odd-numbered paraffins. This fact could provide a useful way to determine the renewable diesel content in a blend of petroleum diesel fuel.

Various terminology is used to define the biodistillates produced via hydroprocessing. Besides "NExBTL," other common terms are Renewable Diesel, Green Diesel, and hydrotreated vegetable oil (HVO). (In this report, we refer to all these materials as "renewable diesel.") These products all share

several important advantages over conventional biodiesel – including higher mass energy content, improved oxidative stability, complete absence of sulfur and nitrogen, and blending behavior that is totally compatible with petroleum diesel blendstocks. Additionally, the properties of renewable diesel do not vary with feedstock composition as significantly as do the properties of biodiesel.

Lack of glycerol production is a significant benefit of all renewable diesel production processes. In addition, no alcohol is required for this process. Furthermore, production of renewable diesel within a petroleum refinery allows for betterintegration with other refinery operations, and provides access to product testing laboratories. Finally, hydroprocessed biodistillates may exhibit emissions advantages over conventional biodiesel, though the evidence for this is rather limited.



Figure 23. Hydroprocessing of Triglycerides

One disadvantage of hydroprocessed biodistillates is their relatively poor lubricity characteristics. In this regard, they are similar to ULSD, or to paraffinic blendstocks produced by Fischer-Tropsch (FT) or other GTL processes. All these materials generally require additive treatment, or mixing with higher lubricity blendstocks, to achieve satisfactory performance. Other disadvantages of renewable diesel production include the need for additional hydrogen within the refinery, and the high capital cost of hydroprocessing equipment.
4.3 Pyrolysis

In this review, the term "pyrolysis" is used quite broadly to include a variety of processing technologies by which organic feedstocks are treated with heat to break them down to smaller molecules. In the broadest sense, this definition could also include gasification and Fischer-Tropsch (FT) processes by which organic feedstocks (fossil or biomass) are converted to liquid fuels via intermediate production of synthesis gas (syngas). The topic area of gas-to-liquids (GTL) is vast, and well beyond the scope of this review on biodistillates. However, several types of pyrolysis applications that are of direct relevance to our topic of interest are discussed below.

4.3.1 Pyrolysis of Triglycerides

The literature contains many reports of pyrolysis (or thermal cracking) used to treat triglycerides as an alternative to conventional transesterification.^(127,94,93) This option may be advantageous when dealing with low-quality triglyceride feedstocks, which are difficult to treat via transesterification. In thermal cracking processing, the oxygen originally present in the triglyceride is largely removed in the form of CO, CO₂, and H₂O – leaving hydrocarbons, which after further upgrading may be suitable mid-distillate components.^(185,186)

A recent publication has reported on the thermal cracking of triglycerides that are co-fed with conventional petroleum feedstocks used in a fluidized catalytic cracker (FCC).⁽¹⁸⁷⁾ Besides cracking the triglycerides into smaller fragments, considerable rearrangement and aromatization occurs, producing hydrocarbons suitable for both gasoline and diesel blending. While still at the R&D stage, this approach may eventually provide another means of utilizing triglyceride feedstocks within a petroleum refinery to produce conventional transportation fuels (both gasoline and diesel).

Another approach to pyrolyzing triglycerides involves treatment of the entire plant seed, not just treatment of the oil that has been extracted from the seed.^(188,189) Typical oil seeds – such as rapeseed, safflower seed, and soybeans – may contain only 20-40% triglyceride oil, with the remainder being protein, cellulose, and other materials. It has been reported that by treating the entire seed, a pyrolysis oil yield of up to 68% was achieved.⁽¹⁸⁸⁾ However, oils produced in this way require further refining before they are suitable for blending into diesel fuel. To our knowledge, the approach of pyrolyzing whole oil seeds has only been applied to small-scale R&D applications.

4.3.2 Gasification and Pyrolysis of Lignocellulose

Gasification and pyrolysis of lignocellulose to produce liquid transportation fuels are extremely active areas of research. A review of this area is outside the scope of the present study, though we refer the interested reader to two very useful sources of information on this topic.^(2,190) Significant problems with these pyrolysis approaches remain to be overcome – particularly effective means of avoiding char formation, and stabilizing the pyrolysis oils that are produced. Pyrolysis oils produced from lignocellulosic feedstocks contain appreciable levels of oxygen, and are highly reactive, requiring considerable upgrading to be used as transportation fuels.

One interesting approach recently published used biodiesel fuel (FAME) to extract pyrolysis oil produced from treatment of wood chips.⁽¹⁹¹⁾ Potentially, this approach could extend the supply of biodistillates, though the suitability of extracted pyrolysis oil components as transportation fuels has not been demonstrated.

4.3.3 Other Thermal Processes

Several other thermal processes for producing biodistillates are in existence or under development, though obtaining reliable information about most of them is quite difficult. One process, developed by Changing World Technologies, Inc. (CWT) is in commercial operation. This is called Thermal Conversion Process (TCP), though it is also known as the Thermal De-Polymerization (TDP) Process.

In the TCP process, organic materials – such as sewage sludge, offal, shredder residues, plastics, and others – are treated through a multi-stage process involving varying temperatures, pressures, and water contents. Though chemical details are not known, it is likely that TCP involves hydrolysis, decarboxylation, and de-polymerization reactions. The products produced from this process include a combustible gas (generally used within the process itself), a liquid hydrocarbon oil, and a solid residue that can be used as a fertilizer or soil amendment.

A commercial plant utilizing the TCP process is in operation in Carthage, Missouri. According to the CWT website, the feedstock being utilized consists of turkey offal and fats.⁽¹⁹²⁾ This plant has a capacity of 250 tpd of feedstock, which produces approximately 500 barrels/day of fuel oil. More information about CWT's TCP process is available in the patent literature.^(193,194,195)

The oil produced at CWT's Carthage plant has a reported energy content of 18,800 BTU/lb, which is similar to petroleum diesel, suggesting that the oxygen content is quite low. Although this fuel is referred to as "Renewable Diesel," it is unlikely to meet all applicable ASTM specifications for ULSD. It may be more appropriate to consider this product as a diesel blendstock.

Another thermal process has been developed and is being marketed by a company called EcoKat Applied Technologies. (A predecessor company was known as Alphakat.) This technology, called catalytic pressureless deploymerization, is known by its German abbreviation, KDV. In the KDV process, various organic waste feedstocks are mixed with a catalyst (alkali-doped aluminum silicate) and heated to 300-400°C at atmospheric pressure. Under these conditions, the organic feedstocks undergo de-polymerization reactions, producing a diesel-like hydrocarbon product. An innovation of this process is use of high agitation pumps and mixers to provide an internal source of frictional heat that minimizes coking and sludge formation.

The liquid hydrocarbon product produced by EcoKat's KDV process is called Renewable Diesel, but as with the CWT product described above, it may be more appropriate to consider it a diesel blendstock. According to their website, EcoKat has small-scale plants (<100 bpd) operating in Germany, Mexico, and Canada.⁽¹⁹⁶⁾ Further information about the KDV process can be obtained from the patent literature.⁽¹⁹⁷⁾

4.4 Maturity of Biodistillate Production Technologies

All technologies for producing biodistillate fuels are not equally mature. For example, transesterification of vegetable oils to produce FAME is well established, and has been in commercial application for many years. In contrast, gasification and pyrolysis of lignocellulosic feedstocks are far from commercialization. Figure 24 presents our assessment of the technology status for biodistillate production. The progression from laboratory, to pilot plant, to demonstration, to commercialization requires differing amounts of time for each situation. However, in a general case, 2-5 years would be required for each step.

Technology/Feedstock	Laboratory Scale	Pilot Plant Scale	Demonstration Scale	Commercial Scale
Transesterification edible oils/fats non-edible oils microalgae				
Hydroprocessing edible oils/fats non-edible oils microalgae		→ →		
Pyrolysis/Gasification oils/fats organic wastes lignocellulose				

Status of Technologies for Biodistillate Production

Figure 24. Status of Technologies for Biodistillate Production

5. Fuel Properties and Specification

Biodiesel fuel consists of mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats. Since these oils and fats are quite varied in their composition, biodiesel fuels prepared from them also have variable composition. In contrast, the compositions of renewable diesel fuels are less closely tied to their feedstocks, since the hydroprocessing conditions used produce completely saturated paraffins.

In this section, we define the chemical composition of typical biodistillates and their precursors, summarize important physical and chemical properties of these materials, and highlight fuel specifications that have been established by various standard-setting organizations. In addition, we describe several physical and chemical treatments of biodiesel that have been reported to improve certain fuel properties.

Consisting of oxygenated species, biodiesel differs from petroleum diesel in many respects. Some of the most important areas of difference are illustrated below in Table VII, which compares typical properties of biodiesel and petroleum-derived No. 2 ULSD. Also shown here are typical properties of renewable diesel. The property values shown in Table VII were derived by compositing information from several literature sources.^(178,176,177,175,198,199,200) The properties of individual fuels can vary from those shown here.

Because of its considerable oxygen content, biodiesel has lower carbon and hydrogen contents compared to diesel fuel, resulting in about a 10% lower mass energy content. However, due to biodiesel's higher fuel density, its volumetric energy content is only about 5-6% lower than petroleum diesel. Typically, biodiesel has somewhat higher molecular weight than petroleum diesel, which is reflected in slightly higher distillation temperatures (as measured by T_{90}). Being largely straight chain esters, most biodiesel fuels have excellent cetane numbers – typically higher than No. 2 diesel fuel. The viscosity of most biodiesel fuels is significantly higher than petroleum diesel, often by a factor of 2.

Property	No. 2 Petroleum ULSD	Biodiesel (FAME)	Renewable Diesel
Carbon, wt%	86.8	76.2	84.9
Hydrogen, wt%	13.2	12.6	15.1
Oxygen, wt%	0.0	11.2	0.0
Specific Gravity	0.85	0.88	0.78
Cetane No.	40-45	45-55	70-90
T _{90,} °C	300-330	330-360	290-300
Viscosity, mm ² /sec. @ 40°C	2-3	4-5	3-4
Energy Content (LHV)			
Mass basis, MJ/kg	43	39	44
Mass basis, BTU/lb.	18,500	16,600	18,900
Vol. basis, 1000 BTU/gal	130	121	122

Table VII. Typical Properties of Petroleum Diesel and Biodistillate Fuels

Renewable diesel consists mainly of paraffinic hydrocarbons having 15 or 17 carbon atoms. While some renewable diesel fuels contain primarily straight-chain, normal paraffins, others contain appreciable amounts of branched paraffins. As a consequence of their paraffinic structure, renewable diesel fuels have very high cetane numbers and excellent combustion properties. On a mass basis, the energy content of renewable diesel is very high, slightly exceeding that of typical No. 2 diesel fuel. However, due to its relatively low density, the volumetric energy content of renewable diesel is significantly below that of No. 2 diesel, but is similar to a typical biodiesel.

5.1 Chemical Composition of Biodiesel

In large part, the physical properties, performance attributes, and overall suitability of biodiesel are determined by the fuel's chemical composition. The two most important compositional factors are fatty acid chain length and the degree of unsaturation in the fatty acid chain. Unlike petroleum diesel, biodiesel contains virtually no branched chain paraffinic structures, naphthenes, or aromatics. Thus, in some respects, the composition of biodiesel is much simpler than that of petroleum diesel.

A simple naming convention has been developed and is widely used to identify these two main compositional features of fatty acids (and esters prepared from them). This convention consists of two numbers, with the first representing the number of carbon atoms in the fatty acid chain, and the second number representing the number of carbon-carbon double bonds. Following this convention, the four most common C_{18} fatty acids (stearic, oleic, linoleic, and linolenic) are referred to as 18:0, 18:1, 18:2, and 18:3, as they contain 0, 1, 2, and 3 double bonds, respectively.

Table VIII below provides chemical information and structures for 13 of the most common fatty acid precursors to biodiesel. A more comprehensive table is included as Appendix IV-1. These common materials range from 12 to 22 carbon atoms, with varying degrees of unsaturation in the carbon chains. As illustrated in this table, the dominant double bond orientation in these fatty acids is *cis* (or "Z"). The *cis* orientation has important consequences for biodiesel properties, as the alternative *trans* orientation leads to much higher melting points and low temperature performance problems.

Table VIII.	Common Fatty	Acid Precursors	to Biodistillates
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Common Name	Formal Name	CAS. No.	Abbre- viation	Molecular Formula	Molecular Weight	Molecular Structure
Lauric Acid	Dodecanoic acid	143-07-7	12:0	$C_{12}H_{24}O_2$	200.32	ОН
Myristic Acid	Tetradecanoic Acid	544-63-8	14:0	C ₁₄ H ₂₈ O ₂	228.38	ОН
Myristoleic Acid	cis-9- Tetradecenoic Acid	544-64-9	14:1	C ₁₄ H ₂₆ O ₂	226.26	оон
Palmitic Acid	Hexadecanoic Acid	57-10-3	16:0	$C_{16}H_{32}O_2$	256.43	о Пон
Palmitoleic Acid	cis-9- Hexadecanoic Acid	373-49-9	16:1	C ₁₆ H ₃₀ O ₂	254.42	о о о
Stearic Acid	Octadecanoic Acid	57-11-4	18:0	$C_{18}H_{36}O_2$	284.48	ОН
Oleic Acid	cis-9- Octadecenoic Acid	112-80-1	18:1	C ₁₈ H ₃₄ O ₂	282.47	о он
Linoleic Acid	cis-9,12- Octadecadienoic Acid	60-33-3	18:2	$C_{18}H_{32}O_2$	280.46	о Полиника Салания С
Linolenic Acid	cis-9,12,15- Octadecatrienoic Acid	463-40-1	18:3	$C_{18}H_{30}O_2$	278.44	O U OH
Arachidic Acid	Eicosanoic Acid	506-30-9	20:0	$C_{20}H_{40}O_2$	312.54	он
Gondoic Acid	cis-11- Eicosenoic Acid	5561-99-9	20:1	$C_{20}H_{38}O_2$	310.53	OH OH
Behenic Acid	Docosanoic Acid	112-85-6	22:0	C ₂₂ H ₄₄ O ₂	340.60	ОН
Erucic Acid	cis-13- Docosenoic Acid	112-86-7	22:1	$C_{22}H_{42}O_2$	338.58	ОН

Vegetable oils and animal fats contain fatty acid moieties in the form of triglycerides. As mentioned previously, there are hundreds of different seed oils and fats that have been investigated as biodiesel precursors. Compositional information that we obtained from the literature is shown in Appendix IV-2 for several dozen of these triglycerides. However, several limitations of these data should be mentioned:

• First, a particular named oil or fat may exhibit considerable compositional variability from one sample to another. A good illustration of this is soybean oil, which has reported oleic acid content (18:1) ranging from 20% to 80%.

- Second, the chemical compositional data reported in the literature were obtained from dozens of different sources, using many different analytical methods. The data shown in Appendix IV-2 simply summarize the analytical results as reported, without any attempt to harmonize or adjust them for variations in methodology.
- Third, the compositions of many of the more exotic seed oils shown in Appendix IV-2 are based on only 1 or 2 literature sources (often using questionable analytical methodologies). Thus, there may be considerable uncertainty for some of the reported compositions.

Even with the above-mentioned caveats, a few important compositional features are apparent, particularly with respect to carbon chain length and degree of unsaturation. One obvious feature is that all common triglycerides are dominated by even-numbered carbon chains, with C_{16} and C_{18} being the largest components. (Renewable diesel, produced by catalytic hydroprocessing of triglycerides, therefore contains significant amounts of C_{15} and C_{17} molecules, since much of the carboxyl carbon within each fatty acid is removed during this processing.) Another important feature is that some oils are dominated by saturated carbon chains, while others are dominated by unsaturated chains. Examples of this extreme diversity are provided by coconut oil, which is about 90% saturated (mainly C_{12}) and safflower seed oil, which is about 90% unsaturated (mainly C_{12}).

A further illustration of this compositional variability is presented in Fig. 25, which graphically depicts the composition of 8 biodiesel precursors. This shows that the two most commonly used biodiesel feedstocks (soybean oil in the U.S.; rapeseed oil in Europe) differ significantly in their relative compositions of C_{18} fatty acids, with soybean being dominated by linoleic acid (18:2) and rapeseed being dominated by oleic acid (18:1). This compositional difference leads to differences in fuel properties (especially oxidative stability) as will be discussed later. [Although not shown in Fig. 25, it should be mentioned that there are other species of rapeseed that contain substantial levels of erucic acid (22:1), which can contribute to poor low temperature handling.] It is also evident from Fig. 25 that palm oil, coconut oil, and beef tallow all contain high concentrations of saturated carbon chains. This has implications with respect to hydrogen requirements during catalytic hydroprocessing, and with respect to low temperature operation.

5.2. Physical Properties of Biodistillates and their Precursors

As already mentioned, hundreds of vegetable oils and animal fats have been investigated as feedstocks for production of biodiesel. Important physical properties of many of these feedstocks are given in Appendix IV-3; properties of biodistillates (FAME and renewable diesel) are given in Appendix IV-4.

One of the most critical properties of triglyceride feedstocks is viscosity at 40°C, which typically ranges from 20 to 50 mm²/sec, or about an order of magnitude higher than biodiesel FAME or petroleum diesel. The mass energy content (also called lower heating value) of most triglyceride feedstocks is similar to FAME, but 5-10% below the energy content of No. 2 petroleum diesel or renewable diesel.

Due to their considerably higher molecular weight (MW), the flash points of triglyceride feedstocks are much higher than for FAME or petroleum diesel. At the same time, this higher MW leads to poorer low temperature operability for triglycerides (as measured by higher cloud point and pour point) compared to FAME, petroleum diesel, and renewable diesel.



Figure 25. Compositional Profiles of Common Triglycerides

5.3 Biodistillate Fuel Standards

Several standard-setting organizations have developed sets of standard specifications to define acceptable quality of biodistillate fuels. The two most widely accepted organizations are ASTM (in the U.S.) and the European Committee for Standardization (CEN). ASTM has established standard specifications for biodiesel fuel blendstocks (B100) for middle distillate fuels, called ASTM D 6751,⁽³⁾ as well as for biodiesel blends of B6 to B20 in petroleum diesel, called ASTM D 7467.⁽²⁰¹⁾ The CEN has only established standard specifications for B100, called EN 14214.⁽²⁰²⁾ In addition, a consortium of international automobile and engine manufacturers has issued a set of guidelines for biodiesel quality, known as the Worldwide Fuel Charter.⁽²⁰³⁾

Important aspects of the biodiesel (B100) specifications are shown in Table IX. Table X shows the same biodiesel specifications, along with B100 specifications from other countries, ASTM specifications for biodiesel blends (B6-B20) and standard specifications for petroleum diesel in the U.S. and Europe. At the present time, only the U.S. has established a separate standard for biodiesel blends – ASTM D7467 is applicable to blends of B6 to B20. Recently, the U.S. Standard specifications for conventional No. 2 diesel fuel, ASTM D975, were modified to permit low level blends of biodiesel – B5 and below. Also, the European standard specifications for conventional No. 2 diesel fuel (EN 590) are being modified to allow for low level blends of biodiesel. No special standards have been established for renewable diesel, but diesel fuel containing renewable diesel must comply with the appropriate standards for No. 2 diesel fuel (ASTM D 975 in the U.S.; EN 590 in Europe).

A major reason for many of the specifications in the B100 standards is to ensure high purity FAME, free of contaminants and unreacted starting materials that could lead to poor performance with respect to storage stability, injection quality, corrosion, deposit formation, emissions, or other aspects. Further explanation of the ASTM B100 specifications – including rationale for their establishment – is provided below, as well as some comparisons with European and other fuel specifications. This information was obtained from several literature sources, ^(107,198,201,199,200) as well as from the fuel standard documents themselves.

5.3.1 Water and Sediment

B100 should be clear in appearance and free of water and sediment. A centrifuge-based test method, D 2709, is used to determine the cleanliness of the fuel. The same test is used for both B100 and petroleum diesel (as defined in D 975). In both cases, the acceptable maximum limit of water and sediment is 0.05 vol.%.

For several reasons, this is a very important test for B100. For example, available water can react with FAME to produce fatty acids, can support microbial growth in storage tanks, and can lead to excessive corrosion. As described earlier (Section 4) water is formed by certain side reactions (saponification and esterification of free fatty acids) that occur during the production of FAME. Also, water is deliberately added during the washing process to purify the produced biodiesel.

Sediments are of concern because of the potential to plug fuel filters and adversely affect the performance of fuel injectors. Modern fuel injectors operate under extremely high pressures, up to 200 MPa, ⁽¹⁹⁹⁾which requires very small orifice sizes and component clearances. Proper functioning of these fuel injectors is jeopardized by excessive sediment levels, potentially leading to engine damage.

Droporty	ASTM D 67	51-08	l	EN 14214	Worldy	wide Fuel Charter Guidelines	
Property	Limits	Method	Limits	Limits Method		Method	
Water and Sediment (% vol., max)	0.05	D 2709	0.05 EN 12937 ^g		0.05	D 2709	
Total Contamination (mg/kg, max.)			24	EN 12662	24	EN 12662, D 2276, D 5452, D 6217	
Kinematic Viscosity @ 40° C (mm ² /s)	1.9-6.0	D 445	3.5-5.0	EN 3104/3105	2.0 - 5.0	EN 3104, D 445,	
Flash Point, Closed Cup (°C, min.)	93	D 93	120	EN 3679	100	ISO 2719, D 93	
Methanol (wt.%, max.)	0.20 ^a	EN 14110	0.20	EN 14110	0.20	EN 14110,	
Cetane No. (min.)	47	D 613	51	EN 5165	51	ISO 5165, D 613,	
Cloud Point (°C)	Report ^d	D 2500	Col	untry Specific			
Sulfated Ash (wt.%, max.)	0.020	D 874	0.020	EN 3987	0.005	EN 6245, D 482,	
Total Ash (wt.%, max.)					0.001	EN 6245, D 482,	
Gp I metals Na + K (mg/kg, max.)	5	EN 14538	5	EN 14108/14109	5	EN 14108/14109, EN 14538	
Gp II Metals Ca + Mg (mg/kg, max.)	5	EN 14538	5	prEN 14538	5	EN 14538	
Total Sulfur (ppm, max.)	15 ^b	D 5453	10	EN 20846	10	EN 20846/20884, D 5453, D 2622	
Phosphorous (ppm, max.)	10	D 4951	10	EN 14107	4	EN 14107, D 4951, D 3231	
Acid No. (mg KOH/g, max.)	0.50	D 664	0.50	EN 14104	0.50	EN 6618, EN 14104, D 664, D 974,	
Carbon Residue (wt. %, max)	0.05	D 4530	0.30 ^e	EN 10370	0.05	D 4530	
Free Glycerin (wt.%, max.)	0.02	D 6584	0.02	EN 14105/14106	0.02	EN 14105/14106, D 6584	
Total Glycerin (wt.%, max.)	0.24	D 6584	0.25	EN 14105	0.24	EN 14105, D 6584	
Mono Glyceride (wt.%, max)			0.80	EN 14105	0.80	EN 14105	
Di glyceride (wt.%, max)			0.20	EN 14105	0.20	EN 14105	
Triglyceride (wt.%, max)			0.20	EN 14105	0.20	EN 14105	
Distillation (T-90 °C, max.)	360 °	D 1160					
Copper strip corrosion (3-hr. at 50° C, max.)	No. 3	D 130	No. 1	EN 2160	Light Rusting	D 665-Procedure A	
Oxidation Stability (hrs @ 110°C, min)	3	EN 14112	6	EN 14112	10	EN 14112, prEN 15751	
Linolenic acid methyl ester (wt.%, max)			12	EN 14103	12	EN 14103 mod	
Polyunsaturated acid methyl esters (wt.%,max)			1	prEN 15799	1	prEN 15799	
Ester Content (wt.%, min)			96.5	96.5 EN 14103		EN 14103 mod, EN 14078	
lodine Number (gl/100g, max.)			120	EN 14111	130	EN 14111, prEN 15751	
Density (kg/m ³)			860-900	EN 3675	860-900	EN 3675, D 4052, EN 12185	
Cold Soak Filterability (seconds, max.)	360 ^f	Annex A1					

Table IX. U.S. and European Biodiesel Standards (B100)

Footnotes:

a Alternatively, flash point must be > 130 °C

b For blending with ULSD. For other fuels, higher sulfur levels are allowed

c Atmospheric equivalent T-90 point

d Low temperature properties are not strictly specified, but should be agreed upon by the fuel supplier or purchaser

e This limit is based on the bottom 10% fraction of the fuel, not the entire fuel

f 200 seconds max. for use in diesel blends at low temperature (< -12°C)

g Method EN 12937 measures total water, but not sediment

Table X. Selected Biodiesel and Diesel Standards

	Biodiesel Fuels (B100)						Biodiesel Blends	N	lo. 2 Diesel	Fuels
Property	U.S. (ASTM D6751-08)	Europe (EN 14214)	Worldwide Fuel Charter	South Africa	Brazil	Japan (JIS K2390)	U.S. (ASTM D7467-08 ^{d)}	Europe (EN 590)	U.S. (ASTM D975)	Worldwide Fuel Charter (Category 4)
Water and Sediment (% Vol., max)	0.05	.05 w/w	0.05 w/w	0.02	0.02	0.05	0.05	0.02 w/w	0.05	.02 w/w
Total Contamination (ppm, max)		24	24	24		24		24		10
Kinematic Viscosity @ 40° C (mm ² /s)	1.9-6.0	3.5-5.0	2.0 - 5.0	3.5 - 5.0		3.5-5.0	1.9-4.1	2.0-4.5	1.9-4.1	2.0 - 4.0
Flash Point, Closed Cup (°C, min.)	93	120	100	100	100	120	52	55	52	55
Methanol (wt.%, max.)	0.20 ^ª	0.2	0.2	0.2		0.2				
Cetane No. (min.)	47	51	51	45	45	51	40	46	40	55
Cetane Index, (min.)						51	40 ^b		40 ^b	55
Cloud Point (°C)	Report ^e	Country Specific			Report	Report	Report ^e		Report ^e	
Sulfated Ash (wt.%, max.)	0.02	0.02	0.005	0.02	0.02	0.02	0.01	0.01		
Total Ash (wt.%, max.)			0.001					0.01	0.01	0.001
Gp I metals Na + K (mg/kg, max.)	5	5	5	10	10	5				
Gp II Metals Ca + Mg (mg/kg, max.)	5	5	5	5		5				
Total Sulfur (ppm, max.)	15	10	10	10	10	10	15	50	15	10
Phosphorous (ppm, max.)	10	10	4	10	10	10				
Acid No. (mg KOH/g, max.)	0.5	0.5	0.5	0.8	0.8	0.5	0.3			0.08
Carbon Residue (wt.%, max)	0.05	0.3	0.05	0.05	0.05	0.3	0.35	0.3	0.35	0.2
Free Glycerin (wt.%, max.)	0.02	0.02	0.02	0.02	0.02	0.02				
Total Glycerin (wt.%, max.)	0.24	0.25	0.24	0.38	0.38	0.25				
Mono Glyceride (wt.%, max)		0.8	0.8	1.00	1.00	0.8				
Diglyceride (wt.%, max)		0.2	0.2	0.25	0.25	0.2				
Triglyceride (wt.%, max)		0.2	0.2	0.2	0.25	0.2				
Distillation (T-90 °C, max.)	360 °			360 @ T95	360 @T95	360	343	360	282-338	320
Copper strip corrosion (3-hr.@ 50° C, max.)	No. 3	No. 1	Light Rusting	No. 1	No. 1	No. 1	No. 3	No. 1	No. 3	No. 1
Oxidation Stability (hrs @ 110°C, min)	3	6	10	6	6	2	6			
Linolenic acid methyl ester (wt.%, max)		12	12	12		12				
Polyunsaturated methyl esters (wt.%, max)		1	1	1		1				
Ester Content (wt.%, min)		96.5 min.	96.5 min	96.5 min		96.5 min	6-20 vol.%	0 - 5		
lodine Number (g l ₂ /100g, max.)		120	130	140		120				
Density (kg/m ³)		860-900	860-900	860		860 - 900		820-845		820 - 840
Aromatics (% vol., max)							35 ⁵		35 ^b	15 % m/m
Lubricity @ 60 °C, WSD, microns (max)							520	460	520	400
Polycyclic Aromatic Hydrocarbons (wt.%, max)								11		
Cold Soak Filterability, (seconds, max)	360 ^f									

Footnotes

- a. Alternatively, flash point must be > 130 °C
- b. Either aromatics spec or Cetane Index spec (40, min) must be met
- c. Atmospheric equivalent T-90 point

- d Biodiesel component of the blend must conform to requirements of ASTM D6751
- e Low temperature properties are not strictly specified, but should be agreed upon by the fuel supplier or purchaser
- f 200 seconds max for use in diesel blends at low temperature (< -12°C)

The European Biodiesel Standard (EN 14214) includes test method EN 12937, that measures total water. In addition, the European standards include a specification for "Total Contamination," Method EN 12662, which is a mass-based determination of non-water solid contaminants in the fuel. The maximum allowable level of such contaminants is 24 mg/kg. The U.S. standards do not include a comparable specification for total contamination.

5.3.2 Kinematic Viscosity

According to ASTM D 6751, test method ASTM D 445 is required to determine the viscosity of B100. This is done by measuring the time required for a specific volume of the sample to flow through a prescribed capillary tube under gravity. As viscosity is highly dependent upon temperature (see Fig. 16), the temperature of this test is carefully controlled at 40°C.

Viscosity affects the behavior of fuel injection, with high viscosity leading to larger droplet size, poorer atomization, and greater in-cylinder penetration of the fuel spray. These conditions can also lead to engine deposit formation, poor combustion, higher emissions, and increased engine oil dilution.

As previously mentioned, triglyceride oils and fats have unacceptably high viscosity levels, which prevent them from being used as neat fuels. Biodiesel fuels produced from these triglycerides have considerably reduced viscosity levels, but they still typically exceed the levels of No. 2 diesel fuel. Because of this, the allowable viscosity limits for B100 are slightly higher than for petroleum diesel. The ASTM standards specify a viscosity range of $1.9 - 4.1 \text{ mm}^2$ /sec for petroleum diesel, but a larger range of $1.9 - 6.0 \text{ mm}^2$ /sec for B100. [Note: the units used to express viscosity, mm²/sec, are sometimes referred to as centistokes (cSt).] The European B100 standards are somewhat more restrictive, having a narrower acceptable viscosity range of $3.5 - 5.0 \text{ mm}^2$ /sec.

5.3.3 Flash Point

Flash point is determined by ASTM D 93, which involves slowly heating a sample of fuel in a closed, stirred cup. The cup is opened at various time intervals, and an ignition source is moved over the top of the cup. The flash point is defined as the minimum temperature at which the fuel will ignite upon application of this ignition source.

Flash point varies inversely with volatility. The presence of even small amounts of volatile substances can lower the flash point of a fuel substantially. Thus, the flash point specification is used to protect against excessive contamination by methanol, which may be left over from the production of FAME. Besides the safety hazard resulting from a low flash point, excessive methanol can affect fuel pumps, seals, and elastomers, and contribute to decreased lubricity.

The minimum flash point limit in ASTM D 6751 is 93°C. The European biodiesel standard defines a somewhat higher flash point limit of 120°C. These are both substantially higher than the ASTM D 975 limit of 52°C for conventional No. 2 diesel fuel. Consequently, the flash point test for biodiesel is not an effective means of detecting methanol in biodiesel blends.

5.3.4 Methanol Content

As described above, methanol contamination in B100 can contribute to a number of safety and performance problems. Despite this, ASTM D 6751 does not require explicit measurement of methanol. However, if methanol is not measured, the B100 sample must meet a more stringent flash point specification of 130°C. If methanol is measured directly, it is done using a gas chromatographic-based method, EN 14110, which is also required by the European B100 standard. The maximum allowable amount of methanol is 0.02 wt.%, according to both the U.S. and European standards.

5.3.5 Cetane Number

Cetane number is a measure of a fuel's ignition and combustion characteristics. It is determined experimentally in a standardized laboratory engine, by comparing the ignition performance of a test fuel with the performance of other fuel blends having known cetane numbers. A minimum cetane number of 47 is required for B100. This is considerably higher than the cetane number limit of 40 required by ASTM D 975 for conventional No. 2 diesel fuel. The European limit for B100 is higher yet, at 51. However, FAME materials have naturally high cetane numbers, so meeting either the U.S. or European standard is generally not a problem.

For petroleum diesel, a calculated cetane index is sometimes used to define the fuel's combustion characteristics, rather than a measured cetane number. The cetane index calculation is based upon the fuel's specific gravity and distillation curve, both of which are quite different for B100 compared to petroleum diesel. Consequently, the established cetane index calculations are not accurate predictors of cetane number for biodiesel.

5.3.6 Cloud Point

Cloud point is the temperature at which a visible haze of wax crystals first appears in a fuel as it is cooled down under conditions prescribed in ASTM test method D 2500. Cloud point is an important feature in cold weather performance for all distillate fuels. Typically, B100 has higher cloud points than conventional diesel fuel, largely due to the presence of saturated FAME species such as methyl palmitate (16:0) and methyl stearate (18:0). As discussed in later sections, the cloud point of B100 can be modified by use of additives and by blending with other feedstocks.

Despite the importance of cloud point, no numeric standards have been established by either U.S. or European organizations. However, fuel producers are required to measure the fuels' cloud point, and report this to the customer.

5.3.7 Sulfated Ash

ASTM D 874 is used to determine the sulfated ash content of biodiesel. In this test, the sample is ignited and burned until only ash and carbon remain. The residue is then treated with sulfuric acid and heated to completely oxidize and remove all carbon. The remaining sulfated ash is then weighed. According to ASTM D 6751, the maximum allowable amount of sulfated ash in B100 is 0.020 wt.%.

The primary purpose of this sulfated ash procedure is to ensure minimal contamination by the alkaline catalysts used in the esterification method of producing biodiesel; namely sodium (Na) and potassium (K). Excessive levels of Na and K can lead to engine deposits and other harmful consequences. Of particular concern is the susceptibility of modern diesel particulate filters (DPF) to impairment from excessive ash levels. The maximum sulfated ash guideline recommended by the Worldwide Fuel Charter (0.005%) is more restrictive than that allowed by either ASTM D 6751 or EN 14214 (0.020%).

Conventional diesel fuel does not have a specification for sulfated ash, but does have a total ash specification. Total ash is determined by a different method, D 482, and has a maximum allowable level of 0.01 wt.%. This total ash specification also applies to B6-B20 blends, as defined in ASTM D 7467, but does not apply to B100.

5.3.8 Group I and II Metals

As described above, a sulfated ash method (ASTM D 874) is required primarily to determine contamination of biodiesel by Na and K. Another method, EN 14538, is also required to determine the

same Group I metals (Na and K) as well as the Group II metals, calcium (Ca) and magnesium (Mg). Method EN 14538 involves optical emission spectral analyses with inductively coupled plasma (ICP-OES). In this method, Na and K are measured together. The maximum allowable sum of Na and K is 5 ppm. Similarly, Ca and Mg are measured together, and also have a total allowable sum of 5 ppm.

5.3.9 Sulfur Content

The total sulfur content of biodiesel is determined by ASTM Method D 5453. In this method, a small volume of fuel is injected into a high temperature combustion tube, where all the sulfur is converted to SO_2 . The combustion gases are then exposed to UV irradiation that converts SO_2 to a high energy excited form. As this high energy species reverts to its stable state, it emits light which is detected by a photomultiplier tube. The intensity of this fluorescence is proportional to the amount of sulfur in the sample.

Biodiesel meant for blending with ULSD generally meets the ASTM sulfur specification established for ULSD; namely, 15 ppm maximum. The European standard for biodiesel requires a slightly lower maximum of 10 ppm. The major concern about sulfur contamination is its adverse effects on the performance of exhaust emissions control systems. Fortunately, most biodiesel fuel feedstocks are naturally low in sulfur. However, it is possible for sulfur contamination to arise from neutralization agents used in the FAME production process. In addition, some low grade feedstocks such as fats, greases, and used vegetable oils can contain appreciable levels of sulfur.

5.3.10 Phosphorus

The U.S. standard for B100 requires ASTM Method D 4951 to be used in determining total phosphorus (P) concentrations. A maximum limit of 10 ppm P is allowed, which is the same limit specified in the European standard for B100. Method D 4951 involves inductively coupled plasma with atomic emission spectrometry (ICP-AES). The ASTM standards for conventional diesel (D 975) and for B6-B20 blends (D 7467) do not include a specification for phosphorus content.

As with sulfur, the principal concerns about phosphorus contamination are related to emissions control system degradation. (Because of this concern, the Worldwide Fuel Charter recommends a maximum P limit of 4 ppm.) Biodiesel naturally contains very little phosphorus, but some contamination is possible if triglyceride feedstocks are not adequately refined prior to being used in the transesterification process. In particular, some phospholipids can remain in vegetable oils, and proteins can remain in animal fats.

5.3.11 Acid Number

The most common method for determining acid content in biodiesel is ASTM D 664, which involves titration of free fatty acids with a solution of KOH. The maximum allowable limit for acid number is 0.50 mg KOH/g fuel, according to both the U.S. and European standards. ASTM D 7476 (for B6-B20 blends) allows a slightly lower acid number of 0.3 mgKOH/g, while conventional diesel and has no specification for acid number.

The presence of free fatty acids can promote corrosion in fuel injection systems and other metallic components. Generally, freshly prepared biodiesel will have a very low acid number, since the base catalyst used in the transesterification process will remove all available fatty acids. However, upon degradation of the fuel by exposure to water and air, free fatty acids may be produced. The Worldwide Fuel Charter suggests that a change in total acid number (Δ TAN) following an accelerated fuel aging test be used as an indication of fuel stability. So far, no standards-setting organization has adopted a Δ TAN specification.

5.3.12 Carbon Residue

Carbon residue is a measure of how much residual material remains after combustion. This test involves vaporization of the fuel at high temperature (550°C) in the absence of oxygen. For conventional diesel fuel, ASTM D 975 requires use of Method D 524, which first involves removal of 90% of the fuel by distillation. Carbon residue is then determined on the remaining 10% fraction. For No. 2 diesel, the specification limit from this test (often called the Ramsbottom carbon residue) is 0.35 wt% of the 10% bottoms.

When dealing with biodiesel, it is difficult to obtain a 10% bottoms fraction by distillation, so the carbon residue determination is conducted on the neat, undistilled fuel, according to Method D 4530. The maximum carbon residue limit for B100 is 0.05 wt.% of the entire fuel. The same test method and carbon residue limit apply to B6-B20 blends under ASTM Standard D 7467. However, the European B100 standard is based upon a 10% bottoms fraction, and therefore has a higher limit of 0.30 wt%.

While not directly correlating with injector and engine deposits, carbon residue is thought to give a reasonable estimate of the depositing tendencies of a fuel. In biodiesel samples, high levels of carbon residue can be caused by contamination with unreacted glycerides. As discussed below, B100 standards include other specifications to directly address this issue.

5.3.13 Free and Total Glycerin

Free and total glycerin are measured by the same gas chromatographic method, ASTM D 6584, which involves derivatization of the materials to facilitate chromatographic separation and detection. Free glycerin (also called glycerol) results from incomplete separation of the FAME product after transesterification. High levels of free glycerin may cause problems during fuel storage by settling to the bottom of tanks, or in the fuel system by clogging filters and injectors. "Bonded glycerin" refers to monoglycerides, diglycerides, and triglycerides that remain in the fuel due to incomplete transesterification. High levels of these glycerides can lead to injector fouling and can contribute to engine deposits.

The glycerin limits established in ASTM D 6751 for B100 are 0.02 wt.% for free glycerin and 0.24 wt.% for total glycerin. The European Standards are similar, but also have individual limits for monoglycerides, diglycerides, and triglycerides. Neither conventional diesel fuel nor B6-B20 blends of biodiesel have any specifications for glycerin (either free or total).

5.3.14 Distillation Temperature (T90)

For conventional No. 2 diesel fuel, ASTM D 975 establishes both a minimum (282°C) and a maximum (338°C) limit on the 90th percentile distillation point (T_{90}). These limits are not appropriate for B100, which consists of a narrow range of chemical species, and hence exhibits a much narrower distillation range compared to conventional diesel.

Typically, B100 has a slightly higher boiling point than the T_{90} level of conventional diesel. ASTM D 6751 has defined a maximum T_{90} limit of 360°C for biodiesel as a precaution to ensure that the fuel is not contaminated with high boiling material, such as used motor oil. The required test method, D 1160, involves distillation under reduced pressure, but the limit of 360°C is expressed as an atmospheric equivalent boiling point.

The European B100 Standard (EN 14214) does not contain a specification for distillation temperature. B6-B20 blends defined by ASTM D 7467 have a T_{90} maximum limit of 343°C (slightly higher than conventional diesel at 338°C), but do not have a T_{90} minimum.

5.3.15 Copper Strip Corrosion

The copper strip corrosion test, ASTM D 130, is used to determine the corrosiveness of fuels towards copper surfaces. In this test, a polished copper strip is immersed in a fuel sample for 3 hours at 50°C. After removal and washing, the copper strip is qualitatively rated by comparing its appearance with known standards. The limit for B100 specified in ASTM D 6751 is a maximum rating of No. 3. (Higher numbers indicate a greater degree of corrosiveness.) The same test method and limit apply to conventional diesel fuel (ASTM D 975) and B6-B20 blends (ASTM D 7476). The European standards for both conventional diesel and B100 are more stringent, with a maximum allowable rating of No. 1.

The presence of free fatty acids in B100 can contribute to excessive corrosiveness of the fuel. However, as discussed above, B100 standards (both U.S. and European) have other specifications for total acid number, which are generally regarded as being more protective against excessive free fatty acids.

5.3.16 Oxidative Stability

An accelerated oxidation test, EN 14112 (also called the Rancimat Test), is often used to determine the oxidative stability of biodiesel. In this test, a stream of heated air (110°C) is bubbled through a sample of fuel. Volatile oxidation products (such as light organic acids) are carried by the air stream into a vessel containing distilled water. The electrical conductivity of this water is continuously measured until it rises rapidly. The time between the start of test and the point where the conductivity sharply rises is called the induction period. The induction period limit in ASTM D 6751 for B100 is 3 hours. The limit for European B100 (and for B6-B20 blends in the U.S.) is 6 hours. Conventional diesel fuel does not require a specific test for oxidative stability.

Due to their relatively high concentrations of unsaturated compounds, biodiesel fuels can more readily oxidize, forming peroxides and acids. These oxidation species can damage plastics and elastomers, and can contribute to formation of sludges and deposits. Oxidative stability is regarded as one of the most critical fuel quality issues for biodiesel. Due to this concern, the European Biodiesel Standard (EN 14214) also includes a separate specification for linolenic acid methyl esters (which contains 3 double bonds) and for polyunsaturated acid methyl esters (which contain 4 or more double bonds).

5.3.17 Ester Content

ASTM D 6751 includes no specification for ester content of B100. However, a specification is included in ASTM D 7467 for B6-B20 blends. With these blends, an infrared spectrometric method, ASTM D 7371, is required to ensure that the FAME concentrations are in the range of 6 to 20 vol.%. In contrast, the European biodiesel standard does include a specification for minimum FAME content. A gas chromatographic method, EN 14103, is used to ensure a minimum concentration of 96.5 wt.%.

5.3.18 Iodine Number

Iodine number provides a measure of the number of double bonds (or degree of unsaturation) in the FAME molecules. There is a general correlation between unsaturation and oxidative stability. ASTM standards do not include a specification for iodine number, believing that the Rancimat oxidative stability test provides an adequate measure of biodiesel's stability. The European biodiesel standard does contain a specification for iodine number, determined by Method EN 14111. The specification limit is a maximum of 120 mg $I_2/100g$ of fuel.

This iodine number specification has been the source of some controversy. The European maximum limit of 120 is quite restrictive, so that some common FAME feedstocks, such as soybean oil, have difficulty

meeting it. Even more highly unsaturated feedstocks, such as sunflower and safflower, are precluded from use, unless blended with other low-unsaturation FAME materials.

5.3.19 Density

ASTM standards do not include a specification for B100 density, though the European standards do. Neat biodiesel is significantly denser than conventional diesel. Dilution of biodiesel, either deliberately or inadvertently, is likely to reduce its density. As a precautionary measure, a density range of 860 to 900 kg/m³ is specified in EN 14214.

5.3.20 Cold Soak Filterability

A recently recognized problem is that trace levels of sterol glucosides (SG), which occur naturally in fats and vegetable oils, can contribute to filter plugging – especially at low temperatures. These high MW, highly polar species have very low solubility in biodiesel blends, and can be considered "dispersed fine solid particles."⁽²⁰⁴⁾

To address this situation, ASTM is in the process of developing a standard test procedure to assess the filterability of biodiesel. The most recent version of Standard Specifications for Biodiesel (ASTM D 6751-08) includes a test method in Annex 1, "Determination of fuel filter blocking potential of biodiesel blend stock by cold soak laboratory filtration." In this test method, the time required to vacuum filter 300 mL of biodiesel through a 0.7 μ m glass fiber filter is measured. The filtration is done at room temperature (20-22°C) although the fuel is stored at lower temperature (4.4°C) for 16 hours prior to the filtration. The maximum filter time allowed by this test method is 360 seconds, with a shorter time of 200 seconds allowed if the B100 is intended for blending into diesel fuels for use at ambient temperatures below - 12°C.

5.4 Quality Control/Quality Assurance Measures

To ensure satisfactory product quality, biodiesel producers and marketers must have an established quality control/quality assurance (QC/QA) program. In Germany, the Association for Quality Management of Biodiesel (abbreviated AGQM in German) was established in 1999 to deal with in-use fuel quality.⁽²⁰⁵⁾ More recently, the National Biodiesel Board has addressed this concern in the U.S. by establishment of the National Biodiesel Accreditation Commission that oversees and directs the BQ-9000 Quality Management System.⁽²⁷⁾ This Commission has recently issued two sets of requirements: one for B100 producers;⁽²⁰⁶⁾ the other for B100 marketers.⁽²⁰⁷⁾ By following these requirements, the company – not the fuel – receives accreditation.

The BQ-9000 Producers Requirements define acceptable documentation practices, management responsibilities, laboratory operations, sampling and testing methods, fuel blending and loading requirements, and other aspects of a Quality Management System. A BQ-9000 accredited producer must conduct certain fuel specification tests on every production lot of biodiesel, and provide a certificate of analysis (COA) for each lot. The BQ-9000 Marketers Requirements include many of the same elements with respect to documentation, management responsibilities, and laboratory procedures, but also address issues of fuel storage, blending, and distribution.

A critical aspect of fuel quality is establishment and operation of a competent fuel testing laboratory. A minimal level of quality control testing should be conducted at the fuel production site, for every batch of fuel that is produced. This is routinely done for conventional diesel fuel produced at a petroleum refinery, but for small biodiesel production plants, this is not always the case.

Small "Mom and Pop" producers of biodiesel will generally not have the necessary equipment or expertise to conduct the full range of tests specified in ASTM D 6751 for B100. Even in such cases, however, a subset of the most critical QC tests should be conducted on-site for every batch, with other tests being conducted periodically, using outside laboratories. This distinction between critical and less critical QC laboratory testing has been discussed in some detail by Van Gerpen et al., who recommended a set of 8 tests be performed on each biodiesel batch.⁽¹⁰⁷⁾ They also determined that the total capital cost of equipment necessary to conduct these 8 tests was about \$80K (in 2004).

In Table XI, we provide our recommendations for laboratory QC tests that should be conducted to ensure high quality biodiesel. The tests recommended for every batch of B100 are the same ones recommended by Van Gerpen et al., with addition of the Rancimat oxidative stability test and the cold soak filterability test. This list is similar, but not identical, to the BQ-9000 Producer Requirements.

QC Tests to be Conducte	d on Every Batch	QC Tests to be Conducted Periodically			
Property	Test Method	Property	Test Method		
Water and Sediment	D 2709	Cetane Number	D 613		
Viscosity	D 445	Methanol	EN 14110		
Flash Point	D 93	Metals (Na, K, Ca, Mg)	EN 14538		
Cloud Point	D 2500	Total Sulfur	D 5453		
Sulfated Ash	D 874	Phosphorous	D 4951		
Acid Number	D 664	Carbon Residue	D 4530		
Free and Total Glycerin	D 6584	T ₉₀	D 1160		
Copper Strip Corrosion	D 130	Ester Content*	EN 14103		
Oxidative Stability	EN 14112	Iodine Number*	EN 14111		
Cold Soak Filterability	ASTM D 6751-08 Annex A1				

Table XI. QC Laboratory Testing Recommendations for B100

* Only required for European biodiesel

6. In-Use Handling and Performance of Biodistillate Fuels

As described in the above section, some properties of biodiesel differ from those of conventional diesel fuel. Consequently, precautions must be taken to ensure that proper handling practices are followed, so that products having acceptable quality are being delivered to the end user. Because renewable diesel fuel is virtually identical to petroleum-derived mid-distillate blendstocks, and it is generally blended into a final fuel at the refinery, the issues and practices described in this section pertain mainly to biodiesel, not to renewable diesel.

Under special circumstances, B100 may be utilized. However, for use as a transportation fuel, only blends of biodiesel with conventional diesel are recommended. (An exception exists in Germany, where B100 is commonly used as a transportation fuel.) The literature is replete with studies where various blend ratios of biodiesel have been used. For research and development purposes, investigations of wide blending ranges are valuable, since this provides a better understanding of fuel effects on injection behavior, engine performance, emissions, materials compatibility, and other factors. For commercial use, however, a much narrower range of biodiesel blend ratios is desirable.

In the U.S. today, low biodiesel blend levels are most common; especially B2, B5, and B20. (B11 is common in Illinois due to a unique state tax policy.) B2 is occasionally used to provide sufficient lubricity for ULSD to meet ASTM D 975 requirements, though usually it is easier and less expensive to include a synthetic lubricity additive. B20 is the highest blend level specified by ASTM, and is the highest level recommended by many engine and vehicle OEMs for selected models. (Most engine models are not considered B20 compatible.)

As early as 1996, the National Biodiesel Board began to focus on B20 as the preferred blend of biodiesel.⁽²⁰⁸⁾ Many other groups, including DOE, consider B20 to represent a good balance of cost, emissions, cold weather performance, materials compatibility, and solvency.^(198,94,200) Furthermore, B20 (which imparts approximately 2.2% oxygen content to the fuel blend) is the minimum accepted level for vehicle fleets to satisfy the alternative fuel vehicle requirements of the Energy Policy Act (EPAct). Due to its now common usage, B20 is sometimes referred to simply as "biodiesel." However, more accurate terminology distinguishes between biodiesel (B100) and biodiesel blends, such as B20.

B20 blends (and lower concentration blends) are commonly prepared by mixing B100 with conventional diesel fuel at one of three different steps in the distribution chain: (1) blending by the end user, (2) blending by a jobber or distributor who then provides the finished fuel, or (3) blending at a petroleum terminal or rack by the facility operator. Additionally, three different methods of blending are used:

- 1. Splash blending. B100 and diesel fuel are added separately into a fuel delivery truck or individual vehicle fuel tank. Mixing occurs by means of agitation while the vehicle is in motion.
- 2. In-tank blending. B100 and diesel fuel are added separately or at the same time into a mixing tank. Agitation provided by a rapid filling rate may be sufficient to cause adequate mixing, though additional stirring or recirculation may be necessary in some cases.
- 3. In-line blending. B100 is added in pulses or continuously into a flowing stream of diesel fuel as it travels through a pipe or hose to a larger holding tank.

Reasonable care must be taken to ensure adequate blending. Due to biodiesel's significantly higher specific gravity compared to No. 2 diesel fuel (0.88 vs. 0.85), two distinct layers can form if mixing is inadequate. This problem becomes more severe when blending biodiesel with No. 1 diesel fuel, which has even lower specific gravity – typically 0.80.

In-line blending is preferred because it provides the greatest accuracy and control over the blending operation. However, it is also the most expensive method, as it requires use of metered pumps and injector systems. Other precautionary measures to ensure successful blending include use of multiple B100 tanks (with quality testing being performed on the contents of each tank before blending), and maintenance of a constant temperature (70°F) in all biodiesel tanks and blending equipment.⁽²⁰⁹⁾ Additional guidelines regarding blending and handling of biodiesel are provided in recent DOE and NREL documents.^(198,200) A recent study sponsored by the Canadian Trucking Association also highlights challenges and precautions when integrating biodiesel into the infrastructure already used for conventional diesel fuel.⁽²¹⁰⁾

6.1 Fuel Quality Surveys

One of the biggest concerns of the biodiesel industry is the quality of finished fuels being used in the marketplace. The use of poor quality fuels can lead (and has led) to field problems and customer complaints, which reduce public confidence and jeopardize the future of the industry. Steps to address these concerns have been taken in recent years by adoption (or modification) of ASTM Standards D 6751 (for B100) and D 7467 (for B6-B20), and by development of the BQ-9000 Quality Management System.

Another aspect of ensuring overall product quality is application of in-use surveys. The first systematic field survey in the U.S. was conducted by NREL in 2004, and reported in 2005.⁽²¹¹⁾ In this study, 27 samples of B100 and 50 samples of B20 were obtained from blenders and distributors around the country. Based upon questionnaires, it was determined that most blenders and distributors did not conduct product testing of their own, but relied upon the biodiesel manufacturers to ensure fuel quality. Laboratory tests conducted as part of this study showed that 85% of the B100 samples met all ASTM D 6751-03 standard specifications. However, it was noted that only 4 of the 27 samples would meet a minimum inhibition period of 3 hours as measured by the Rancimat oxidation test. (The Rancimat test was not included in ASTM D 6751 at the time of this study, but was added in 2007.) Similar problems with oxidative stability of the B20 samples were noted. This survey also highlighted blending problems in producing B20, as 18 of the 50 samples tested had biodiesel concentrations outside the accepted range of B18-B22 – 7 were considerably higher (maximum of B98) and 11 were considerably lower (minimum of B7).

In 2006, NREL conducted another nationwide fuel quality survey of B100 intended for use as a blendstock.⁽²¹²⁾ Specification testing of 37 B100 samples showed that 59% failed to meet the ASTM D 6751 requirements applicable at this time. The main reasons for failures were excessive levels of total glycerine and low flash point. Such problems suggest insufficient quality control in the production and clean-up of FAME. These results were quite disturbing because they suggested a worsening of B100 quality between the 2004 and 2006 survey periods. Oxidative stability was again pointed out as an area of concern. Although still not a standard specification at the time of this survey, the Rancimat test was conducted on 10 of the 37 B100 samples. Only 3 of these 10 had an induction period in excess of 3 hours (the current specification).

The most recent nationwide B100 quality survey was conducted by NREL in 2007.⁽²¹³⁾ In this case, all known biodiesel producers in the U.S. were approached, with 56 of the 107 producers supplying samples for testing and evaluation. These 56 samples were binned according to producer size, with 25 samples coming from small producers (<0.1 mg/y), 16 samples from medium-sized producers (0.1 - 1.0 mg/y) and 15 samples from large producers (>1.0 mg/y). Results from laboratory specification testing showed that the large producers nearly always met ASTM D 6751 specifications. However, fuels from small and medium-sized producers still had significant failures, with oxidative stability having the highest failure rate at 30%. (The Rancimat oxidative stability test was included in ASTM D 6751 by this time.) It was also noted that B100 produced from used vegetable oils failed the specifications more often than B100 produced from other feedstocks. Based upon certain assumptions regarding production volumes, it was concluded that 90% of B100 produced in the U.S. met all specifications; a significant improvement over previous survey results. However, a point not discussed by the authors is that all B100 samples in the 2007 survey were voluntarily provided by willing producers. This change in procedure could raise questions about sampling bias.

The 2004 biodiesel quality survey conducted by NREL included B20 samples, while the 2006 and 2007 surveys did not. Results from the 2004 survey raised questions about quality control in blending operations, as 36% of the samples had biodiesel contents outside the acceptable range of B18-B22. More recent work by other organizations has also highlighted concerns about blending problems. One study involving analysis of B20 obtained from retail fueling stations in 2007 showed that of the 19 samples tested, 8 were actually <B17, with 4 being <B5.⁽²¹⁴⁾ This study also reinforced concerns about oxidative stability, as 45% of the samples failed to meet the Rancimat test specification.

In another recent report, a ¹⁴C radiocarbon analysis method was developed and applied to U.S. biodiesel samples acquired in 2006.⁽²¹⁵⁾ This method does not measure FAME content directly, but determines the amount of modern carbon (from recently living biological materials) as opposed to fossil carbon. Of the 10 retail B20 samples tested, 6 were actually B10-B17 and 1 was B74.

Measurement of biodiesel blend concentrations has been an area of investigation for many years. Excellent reviews of analytical methods have been published recently.⁽²¹⁶⁾ Commonly used methods include chromatographic, spectroscopic, and wet chemical methods. However, many of these methods are expensive and time consuming. The new U.S. standard for B6-B20 blends (ASTM D 7467-08) specifies use of method D 7371, which utilizes mid-infrared spectroscopy.⁽²⁰¹⁾ Although not widely practiced, it appears possible to include an on-board fuel sensor for real-time determination of biodiesel content. It has been demonstrated that the same type of dielectric-based sensor used for gasoline/ethanol blends provides reasonably accurate measurements of biodiesel/diesel blends.⁽²¹⁷⁾

6.2 Biodiesel Stability

Ensuring satisfactory stability of biodiesel in the market place is an important, but complex problem. No single test method is able to accurately assess the stability with respect to different degradation pathways. In broad terms, chemical reactivity of biodiesel can be described as involving oxidative and thermal processes. Both sets of processes are influenced by the degree of unsaturation (and the configuration of the double bonds) in the fatty acid chain component of FAME. In the field, unstable fuel can lead to increased viscosity, as well as formation of gums, sediment, and other deposits. Further insights into these degradation processes are provided in recent literature reviews on the topic.^(218,219) Having no unsaturated fatty acid chains, renewable diesel is not highly susceptible to these types of degradation.

Oxidative instability is initiated by extraction of a hydrogen atom from a carbon adjacent to a double bond – the so-called allylic position.⁽²²⁰⁾ Following removal of this hydrogen, rapid reaction with molecular oxygen leads to formation of allylic hydroperoxides. Subsequent reactions involving isomerization and radical chain propagation reactions produce numerous secondary oxidation products such as aldehydes, alcohols, and carboxylic acids. FAME molecules containing a carbon that is adjacent to two double bonds (a bis-allylic group) are particularly susceptible to this type of oxidative instability. It is for this reason that the European biodiesel standard (EN 14214) includes a separate specification for linolenic acid methyl ester.

The Rancimat oxidative stability test (EN 14112) is based upon detection of these volatile, secondary oxidation products that result from reaction of biodiesel with oxygen at elevated temperature. This test was developed as an indicator of vegetable oil storage stability, and is generally regarded as a measure of storage stability for biodiesel. However, it may not be an accurate predictor of thermal stability within the hot environment of a vehicle's fuel injection system.⁽²²¹⁾

Thermal polymerization of biodiesel occurs through Diels-Alder reactions, which require the presence of two double bonds in a conjugated configuration. Isomerization of FAME to produce these conjugated structures occurs at much higher temperatures (250-300°C) than encountered in the Rancimat test procedure. Therefore, thermal polymerization is not generally regarded as a serious problem for biodiesel, except in cases where the fuel is repeatedly heated by the engine and recycled to the fuel tank.⁽²¹⁹⁾

Several groups have investigated other laboratory oxidative tests to predict stability of biodiesel under different conditions. A European study utilized the Rancimat test apparatus, but applied numerous conditions of time, temperature, and oxygen levels to better estimate storage and thermal stability.⁽²²¹⁾ Somewhat mixed results were obtained, with no single set of test conditions being ideal. A similar approach using variations of Rancimat tests conditions was recently reported, and mathematical models were developed to predict oxidation stability as a function of temperature.⁽²²²⁾ These oxidative tests provide a measure called "Oil Stability Index" (OSI; sometimes also called "Oxidative Stability Index"). The Rancimat test specified in the U.S. and European biodiesel standards (EN 14112) provides a particular measure of OSI.

A group at Southwest Research Institute (SwRI) explored numerous test methods for assessing biodiesel stability, and concluded that two were most useful: (1) Rancimat test method (EN 14112) and a modification of ASTM D 2274.⁽²²³⁾ D 2274 is an accelerated storage stability test that is often used with conventional diesel, although it is not a requirement under the standard specifications for diesel fuel, D 975. This test involves heating the fuel at 95°C for 16 hours, while oxygen is bubbled through the sample. After this time, the fuel is cooled and filtered to determine the mass of insoluble oxidation products that have been produced. However, FAME is better able to solubilize these oxidation products, which in petroleum diesel would normally be insoluble. This behavior can lead to situations where a seemingly stable B100, when mixed with ULSD, can produce B20 having unacceptable levels of insolubles.^(218,219)

More recently, a group from NREL and SwRI conducted a detailed experimental study on the stability of biodiesel and biodiesel blends.^(224,225) Several samples of B5, B20, and B100 were investigated under conditions meant to represent three real-world aging situations: (1) storage and handling, (2) fuel in a vehicle's tank, and (3) high temperature engine fuel systems. In part, this work was conducted to establish a technical foundation upon which to base specification requirements for biodiesel stability. Results showed that the best predictor of B5 and B20 stability is the inherent stability of the B100 used in making these blends. Using B100 that met the Rancimat test requirement (induction period of longer than 3-hours) was concluded to be an effective way of ensuring satisfactory storage stability of B5 and B20 for up to 1 year.

An extreme illustration of B100 instability was recently published by a group of Japanese researchers, who showed that the oxidative degradation reactions of FAME are highly exothermic.⁽²²⁶⁾ They cautioned that under certain conditions, this could lead to a potential fire risk due to spontaneous ignition of unstable biodiesel.

6.2.1 Anti-Oxidants

Raw vegetable oils are known to contain varying levels of natural anti-oxidants such as tocopherols and carotenoids. These are high-boiling materials that remain unreacted during the transesterification process of producing FAME, but are removed upon distillation of the FAME. Many literature reports indicate that raw FAME has greater oxidative stability than refined (distilled) FAME. However, synthetic anti-oxidants have been found to be much more effective than these natural anti-oxidants.^(219,221,227,228,229)

Effectiveness of anti-oxidants is generally determined using the Rancimat test. Identifying the optimum anti-oxidant formulation and dosage often requires extensive testing, as the results are quite variable from one fuel to another. It has also been noted that FAME produced from old or recycled vegetable oils is less stable than FAME produced from fresh oils.^(228,230) It generally appears that the most effective anti-oxidants for biodiesel include t-butyl hydroquinone (TBHQ) and pyrogallol (1,2,3 tri-hydroxy benzene). Butylated hydroxy toluene (BHT) materials are also somewhat effective, but may not be the preferred additive for biodiesel as they often are for petroleum diesel fuels. Typical dosages of anti-oxidants used in biodiesel range from 200 to 1000 ppm, with little or no enhanced performance observed at higher concentrations.^(219,229)

6.2.2 Other Approaches to Enhance Stability

Fundamentally, biodiesel instability is a consequence of its high degree of unsaturation, particularly polyunsaturation. Attempts have been made to address this by chemical processes that reduce the degree of unsaturation. For example, deliberate oxidative treatments of biodiesel with hydrogen peroxide⁽²³¹⁾ and ozone⁽²³²⁾ have been conducted with claims of improved stability and other properties. However, much more testing and evaluation are required before such practices could be accepted. A different approach involves selective hydrogenation of poly-unsaturated FAME to produce monounsaturated FAME.⁽²³³⁾ This partial hydrogenation is different from the processes used to produce renewable diesel, where total saturation of the double bonds generally occurs. While an attractive concept, partial hydrogenation is far from commercialization, as it has been applied only in the laboratory thus far, using very expensive catalysts.

Another means of reducing the unsaturation of FAME involves nitration by use of nitric acid.⁽²³⁴⁾ In this case, the main goal is not to improve the oxidative stability of the FAME, but to produce nitrated materials that can be used as cetane improvers.

The goal of reducing the poly-unsaturated content of biodiesel is also driving biotechnology efforts to develop modified soybean plants which produce higher concentrations of oleic acid chains (18:1) at the expense of reduced linoleic acid (18:2) and linolenic acid (18:3) chains.^(37,36)

6.3 Low Temperature Operability

For many users, low temperature operability is the greatest biodiesel concern, particularly during cold seasons of the year. Just as with conventional diesel fuel, precautions must be taken to ensure satisfactory low temperature operability of biodiesel and its blends.⁽²⁰⁰⁾ Poor low temperature operability may be exhibited in several ways, but principally by filter plugging due to wax formation, and engine starving due to reduced fuel flow.

As with fuel stability, there is no single best test to assess low temperature operability. U.S. fuel standards do not include explicit specifications for low temperature operability – either for conventional diesel or biodiesel (or blends of the two). However, the fuel seller is generally required to give an indication of low temperature operability by reporting the cloud point (CP) of the fuel. A number of other laboratory tests are commonly used to define low temperature operability of biodiesel (and conventional diesel). These are listed below in Table XII.

Test Name	Abbreviation	Test Method(s)
Cloud Point	CP	EN 23015, ASTM D 2500, ASTM D 5773
Pour Point	PP	ASTM D 97, ASTM D 5949
Cold Filter Plugging Point	CFPP	EN 116, IP 309, ASTM D 6371
Low Temp Filterability Test	LTFT	ASTM D 4539
Wax Appearance Point	WAP	ASTM D 3117
Cold Soak Filterability	-	ASTM D 6751-08 Annex A1

Table XII. Commonly Used Low Temperature Operability Tests for Biodiesel

The Cold Soak Filterability test listed in Table XII is a new ASTM requirement. It differs from the other tests, which are all designed to measure some aspect of wax formation or fuel thickening upon cooling. In contrast, the Cold Soak Filterability test measures the presence of trace levels of insoluble species such as sterol glucosides.⁽²⁰⁴⁾

6.3.1 Factors Influencing Low Temperature Operability

An excellent review of cold weather properties and performance of biodiesel is available in the literature.⁽²³⁵⁾ In addition, a recent NREL publication provides useful guidance for addressing low temperature operability issues, as well as other in-use handling issues.⁽²⁰⁰⁾ Poor operability results from the presence of long-chain, saturated fatty acid esters present in biodiesel. In general, the longer the carbon chain, the higher the melting point, and poorer the low temperature operability. The presence of

carbon–carbon double bonds lowers the melting point of a molecule (hydrocarbon or fatty acid alkyl ester) significantly. Therefore, to a certain degree, there is a trade-off between fuel stability and low temperature operability. With increasing extent of unsaturation, stability decreases but low temperature operability improves.^(236,237)

In large part, the fatty acid composition of the fats and oil precursors to biodiesel dictate the low temperature operability of the final fuels. Feedstocks with highly saturated fatty acid structures (such as palm oil and tallow) produce biodiesels with poor operability; whereas feedstocks with highly unsaturated fatty acid structures (such as rapeseed and safflower oil) have better operability.

The presence of a methyl ester head group lowers the melting point of its parent fatty acid by about 40°C. Thus, FAME has considerably better low temperature operability than do free fatty acids themselves. Replacing methanol with ethanol to produce FAEE results in slightly improved operability, as ethyl esters typically have melting points 5-10°C lower than the comparable methyl esters.^(238,117,239,104,240)

Blending of B100 with conventional diesel often results in non-linear effects with respect to low temperature operability parameters.⁽²⁴¹⁾ Cloud Point (CP) is determined primarily by the presence of saturated fatty acid esters, which crystallize as the temperature is lowered. Unsaturated fatty acid esters serve to solubilize these waxy saturated materials, but when blended with conventional diesel, the solvency effectiveness may be reduced.

Of all the low temperature properties listed above in Table XII, only CP can be defined thermodynamically, as it is governed by solid-liquid equilibrium as a function of temperature. (True equilibrium conditions may not be achieved during the relatively rapid cool-down tests used to measure CP.) CP is the temperature at which the least soluble biodiesel component crystallizes from solution. Thus, in pure biodiesel CP is generally determined by the type and amount of saturated fatty acid esters, with other components of biodiesel having little effect. Several researchers have developed predictive models for CP, based upon these thermodynamic relationships.^(242,243,238) In general, these models show good agreement with laboratory measurements. Also, because of the thermodynamically driven mechanism for crystallization, small amounts of impurities in biodiesel can significantly affect CP. In particular, it has been noted that low concentrations of unreacted monoglycerides and diglycerides increase CP, although PP is not affected.⁽²³⁵⁾

6.3.2 Approaches for Improving Low Temperature Operability

In his literature review, Dunn described 5 general approaches to improving the cold flow properties of biodiesel.⁽²³⁵⁾ Each of these approaches (as well as others) is described below:

6.3.2.1 Blending with Petroleum Diesel

Diluting biodiesel with petroleum diesel is an effective means of improving low temperature operability. As B20 is the most commonly used form of biodiesel in the U.S., this type of dilution is routinely conducted. However, during particularly cold seasons, further dilution may be desirable, thus producing a blend of <B20. Alternatively, blending with No. 1 diesel may be used rather than No. 2 diesel, though cold blending can be difficult due to the large difference in specific gravity between biodiesel and No. 1 diesel fuel. A recent study has concluded that satisfactory blending requires the biodiesel to be kept at least 10°F above its cloud point.⁽²⁴⁴⁾ While dilution with petroleum diesel improves all measures of cold flow, the effect is not linear with all properties. For example, it has been reported that CP and PP decrease nearly linearly with dilution, while CFPP and LTFT are only slightly affected.^(235,245)

6.3.2.2 Use of Commercial Petroleum Diesel Additives

Cold flow improver (CFI) additives have been developed and applied to conventional diesel fuel for many years. These additives are synthetic polymers of various compositions. CFI additives interact with the wax crystals as they form in the fuel, and modify their size, shape, and degree of agglomeration. CFI additives are commonly referred to as pour point depressants, flow improvers, wax modifiers, and paraffin inhibitors. Determining the optimum CFI additive type and dosage for a particular fuel is something of an art, and requires extensive testing. Studies have shown that some CFI additives are very effective in reducing PP of biodiesel blends, but have little or no benefit with respect to CP or LTFT.^(235,246,247,248)

6.3.2.3 Use of New CFI Additives for Biodiesel

Little information is available in the open literature about new CFI additives designed for use in biodiesel. There are reports of using glycerol in the synthesis of highly hindered glycerol ether derivatives, which improve cold flow properties, although only at high concentrations (>1%).⁽¹⁷³⁾

Also reported in the literature is use of ozonized vegetable oil to improve low temperature operability of biodiesel.⁽²⁴⁹⁾ Ozone reacts with the carbon-carbon double bonds in the oils to produce undefined products which, when added to biodiesel at about 1%, significantly reduced PP, although CP was not affected.

Another recent report describes the use of nickel and manganese based additives produced from resinic acids that are by-products in pulp manufacturing.⁽²⁵⁰⁾ While somewhat effective in reducing PP, there are clear disadvantages to using metallic additives.

6.3.2.4 Use of Higher Alcohols for Transesterification

As already mentioned, using ethanol in place of methanol reduces CP of the fatty acid alkyl esters by 5-10°C, and improves overall low temperature operability. Even greater improvement results from use of isopropyl- or butyl-alcohol.^(235,251) Apparently, these bulky head groups disrupt the molecular spacing, increasing disorder and weakening crystal structures. Although this approach is effective, it is usually not economically viable, as methanol is usually much cheaper to use than the higher alcohols.

6.3.2.5 Crystallization Fractionation

Crystallization fractionation is the separation of fatty acid derived materials on the basis of differences in crystallizing (or melting) temperature. Commercial processes for this have been developed in the animal fats and vegetable oils industries, where this practice is sometimes called "de-waxing" or "winterization." Applying these processes to biodiesel on a large scale introduces significant engineering and economic challenges. Other adverse fuel quality impacts can result, as removal of the highest melting point components leaves a biodiesel that is enriched in unsaturated components, thereby decreasing cetane number and oxidative stability. In addition, a commercial outlet for the removed waxy fraction must be found. Nevertheless, crystallization fractionation remains an active area of research. A recent article reported improved efficiency in the process by using micro heat exchangers having very small chamber diameters of 0.2 mm.⁽²⁵²⁾

6.3.2.6 Other Methods

As previously mentioned, genetic engineering approaches are being pursued to develop seed oil compositions that are more favorable for both oxidative stability and for low temperature operability.^(240,236) A different approach, still in the research stage, involves structural isomerization of FAME by reaction with solid acid catalysts.⁽²⁵³⁾ While effective in reducing CP, this approach does not appear to be economically viable at present. However, similar isomerization approaches are being applied

to renewable diesel blendstocks in refinery applications, as a means of improving their low temperature performance.

6.4 Viscosity of Biodiesel

Viscosity is defined as a measure of resistance to flow of a liquid due to internal friction of one part of a fluid moving over another.⁽²⁵⁴⁾ Dynamic viscosity (η) is the ratio of shear stress existing between layers of moving fluid and the rate of shear between the layers.⁽²³⁵⁾ Kinematic viscosity (υ) is the resistance to flow of a liquid under gravity. Kinematic viscosity equals the dynamic viscosity of a fluid divided by its density (ρ); that is $\upsilon = \eta/\rho$.

The viscosity of biodiesel is typically higher than that of petroleum diesel – often by a factor of two. The viscosity of straight vegetable oil is much higher yet, and is the main reason why such oils are unacceptable as diesel blendstocks. Viscosity has significant effects on the injection quality of diesel fuels and fuel blends. In general, the higher the viscosity, the poorer the fuel atomization.⁽²⁵⁵⁾ Higher viscosity has been shown to result in narrower injection spray angle, longer penetration length, and lower fuel vaporization in the combustion chamber.⁽²⁵⁶⁾ Several investigators have shown that with its higher viscosity, biodiesel also produces larger mean droplet sizes upon injection.^(257,258,259) In addition, due to higher viscosity, the delivered fuel volume (or rate of fuel injection) of biodiesel can be lower than with petroleum diesel.⁽²⁶⁰⁾ Alternatively, a higher pressure is required with biodiesel to deliver the same volume of fuel as with petroleum diesel.⁽²⁵⁸⁾

Viscosity can vary among different biodiesel fuels by as much as 100%.⁽²⁵⁷⁾ This may be one reason for the relatively large performance and emissions differences reported in the literature for biodiesel fuels. Also, viscosity is extremely sensitive to temperature, increasing nearly exponentially as temperature is reduced.⁽²⁴⁰⁾ Thus, concerns about poor atomization with biodiesel are exacerbated at low temperature. One recent study has shown that as temperature is reduced, the distribution of B100 fuel among individual injectors within an injector assembly becomes very unequal.⁽²⁶¹⁾ This, in turn, could lead to engine performance and emissions problems.

Viscosity of biodiesel is affected by the compositional make-up of the fuel. In general, viscosity increases with carbon chain length and degree of saturation.^(254,262) Carbon-carbon double bond configuration also influences viscosity, with *cis* configuration giving a lower viscosity than *trans*. Position of the double bonds within the carbon chain, and chain branching, have little effect on viscosity. The alcohol used in transesterification to produce biodiesel also has an influence, as FAEE has slightly higher viscosity than FAME. Empirical models have been developed to predict the viscosity of biodiesel fuels with reasonable success.^(263,264)

Biodiesel users have very few options to improve the viscosity of the fuel. The only practical approaches involve heating the fuel or diluting it with petroleum diesel (or renewable diesel). Low concentration blends of biodiesel (B20 and below) generally have acceptable viscosity, and do not cause significant field problems. The viscosity range specified for B6-B20 blends in ASTM D 7467 is identical to that of ULSD, at 1.9 - 4.1 mm²/s. Adherence to this specification should ensure satisfactory biodiesel quality with respect to viscosity. Exceedance of this viscosity limit is an indication of fuel contamination with unreacted (or partially reacted) vegetable oils,⁽²⁶⁵⁾ or a blending problem causing higher biodiesel contents than B20.

6.5 Lubricity

Lubricity can be defined as the ability to reduce friction between solid surfaces in relative motion.⁽¹⁹⁹⁾ In most applications, two mechanisms contribute to the overall lubricity: (1) hydrodynamic lubrication and (2) boundary lubrication. In hydrodynamic lubrication, a liquid layer (such as diesel fuel within a fuel

injector) prevents contact between opposing surfaces. Boundary lubricants are compounds that adhere to the metallic surfaces, forming a thin, protective anti-wear layer. Boundary lubrication becomes important when the hydrodynamic lubricant has been squeezed out or otherwise removed from between the opposing surfaces.

Good lubricity in diesel fuel is critical to protect fuel injection systems. To provide better engine performance and lower emissions, modern injection systems have become more sophisticated than older systems. For example, not only do today's systems control injection timing, they also have capabilities for injection rate shaping, multiple injections per cycle, pilot injections, and other features. Today's common rail injection systems also operate at much higher pressure than in the past, reaching pressures as high as 200 MPa.⁽¹⁹⁹⁾

In many cases, the fuel itself is the only lubricant within a fuel injector. With the increasing operational demands described above, maintaining adequate lubricity is more critical than ever to ensure satisfactory performance of fuel injection systems. However, as the need for improved lubricity has increased, the natural lubricity of diesel fuels has decreased. This was first noticed in the U.S. following introduction of low sulfur diesel fuel standards in 1993, which established a maximum sulfur limit of 500 ppm for onroad No. 2 diesel fuel.⁽²⁶⁶⁾ (The previous maximum sulfur limit was 5000 ppm.) The refinery hydrotreating processes used to reduce sulfur levels were found to also reduce the fuel's lubricity.^(267,268)

It was discovered that this reduction in lubricity was not due to sulfur removal itself, but to simultaneous removal of trace level lubricity-imparting materials during the hydrotreating processes.^(269,270) Studies have shown that molecules containing hetero-atoms (O, N, and S) generally have improved lubricity compared to hydrocarbons, with oxygen-containing materials being especially effective.⁽²⁷¹⁾ Lubricity effectiveness generally decreases in the order of O>N>S>C. Within the class of oxygen-containing materials, carboxylic acids are more effective than alcohols, esters, and ethers.⁽¹²²⁾ In fact, low concentrations (10-50 ppm) of carboxylic acids are frequently added to petroleum diesel as lubricity improvers.⁽¹⁹⁹⁾

With introduction of ULSD in 2006, having a maximum sulfur limit of 15 ppm, fuel lubricity has become a more critical issue. The extreme degree of hydrotreatment necessary to achieve these low sulfur concentrations effectively removes all other hetero-atom containing molecules, thereby producing a hydrocarbon fuel having very high purity, but low lubricity. Because of this, U.S. standards for No. 2 diesel fuel (ASTM D 975) were recently modified to include a lubricity specification for the first time. This specification is based upon ASTM Method D 6079, which determines lubricity using a High Frequency Reciprocating Rig (HFRR) test apparatus that involves moving a steel ball across a hardened plate immersed in the test fuel. To pass this specification test, the wear scar that appears on the steel ball must be no larger than 520 µm in diameter. An alternative lubricity test is ASTM D 6078, which uses a Scuffing Load Ball on Cylinder Lubricity Evaluator (SL-BOCLE). In some instances, the SL-BOCLE test may provide a better indication of in-use wear than the HFRR test.⁽²⁶⁹⁾

In the U.S., lubricity specifications apply to both conventional diesel and B6-B20 blends of biodiesel. B100 does not have a lubricity specification. In fact, the natural lubricity of neat B100 is so high that a 1% blend of it with ULSD is generally sufficient to meet the lubricity specification of D 975.^(271,200) In part, biodiesel's good lubricity can be attributed to the ester group within the FAME molecules, but a higher degree of lubricity is due to trace impurities in the biodiesel. In particular, free fatty acids and monoglycerides are highly effective lubricants.^(271,272) It has been noted that purification of biodiesel by means of distillation reduces its lubricity because these high-lubricity impurities are removed. The effect of unsaturation upon lubricity is unclear, with some researchers reporting positive effects of carboncarbon double bonds⁽²⁷¹⁾ while others report no effect.⁽²⁷³⁾ Renewable diesel, produced by hydroprocessing of triglycerides, generally has poor lubricity characteristics. In this regard, it is similar to paraffinic blendstocks produced by Fischer-Tropsch (FT) or other gas-to-liquids (GTL) processes. Renewable diesel requires additive treatment, or mixing with higher lubricity blendstocks, to achieve satisfactory lubricity performance.

6.6 Materials Compatibility and Wear

Due to its different physical and chemical properties, introducing biodiesel into systems designed for petroleum diesel raises questions about materials compatibility and other potentially adverse impacts on fuel or engine systems. Some of these issues are discussed below.

6.6.1 Materials Compatibility

The issue of materials compatibility pertains to the impacts of biodiesel upon seals, gaskets, hoses, metal surfaces, and other materials that the fuels contact. It is well known from laboratory studies and in-use experience that changes in fuel composition can affect the integrity of elastomeric materials. In particular, changes in swelling, shrinkage, embrittlement, and tensile strength are of concern, as extreme changes in these properties can lead to seal failures, leaks, and subsequent problems.

Materials compatibility issues are of greatest concern with use of B100, and are another reason why use of B100 is generally discouraged. With B20, these concerns are greatly reduced, but not eliminated. In 2005, the Coordinating Research Council (CRC) sponsored a thorough assessment of materials compatibility using low level blends of biodiesel (B5 and B20) produced from rapeseed methyl ester (RME) and soy methyl ester (SME).^(274,275) To further stress these fuels, some of the SME blends were prepared using B100 that had been deliberately oxidized, using conditions more extreme than are likely to be encountered in the field. Several common fluorocarbon elastomeric materials were immersed in the fuel blends under prescribed conditions and then tested for changes in appearance and physical properties. Two of the five elastomers were reported as being most compatible with the test fuels, though the others may also be acceptable in most applications.

In a similar study,⁽²⁷⁶⁾ researchers from NREL and SwRI investigated the compatibility of five elastomeric materials (in the form of o-rings) with three fuels: (1) baseline certification diesel fuel (having 346 ppm sulfur), (2) baseline fuel blended with 15% ethanol, and (3) baseline fuel blended with 20% soy-based biodiesel. No significant impacts of B20 upon elastomer deterioration were observed, and the authors concluded that all five elastomers appeared to be fully compatible with this fuel. However, the E15 blend did show noticeable deterioration, and may be expected to cause operational problems in certain field applications.

More recently, researchers from DuPont conducted an elastomeric compatibility study with various biodiesel fuels and blends.⁽²⁷⁷⁾ While all the elastomers performed well with fresh, pure biodiesel, severe swelling occurred when the elastomers were exposed to fuels that were contaminated with water and/or free fatty acids. In field use applications, such conditions could be encountered, possibly leading to seal leakage or other operational problems. Both contaminated B20 and B100 fuels were found to be aggressive towards several conventionally-formulated elastomers. This work illustrates the need to formulate elastomeric materials that will be sufficiently durable even under worst case field conditions. The most recent version of NREL's Biodiesel Handling and Use Guidelines provides a comprehensive list and classification of elastomer compatibility with biodiesel.⁽²⁰⁰⁾

6.6.2 Wear Impacts

With its superior lubricity, it might be expected that use of biodiesel would result in lower wear of metal surfaces. The literature contains some information to support this expectation. In a 2003 paper, an Indian

research group conducted long-term engine endurance testing (up to 512 hours) using engines fueled with conventional diesel and biodiesel blends, with rice bran methyl ester being used as biodiesel.⁽²⁷⁸⁾ Periodic sampling and analysis of the lube oil revealed 30% lower concentrations of wear metals from the biodiesel blends. In the same study, a bench rig was used to investigate wear between two rubbing metal surfaces; e.g. a section of piston ring and a section of cylinder lining. Scanning electron microscopy (SEM) showed less surface damage when using B20 compared to conventional diesel fuel.

In a follow-up to this Indian study, more extensive tribological examinations were performed on the used lube oils drawn from engines running on conventional diesel and B20.⁽²⁷⁹⁾ Overall, the condition of the lube oil from the B20 fueled engine was considered superior to that from conventional diesel, containing lower amounts of wear debris, soot, resinous compounds, and oxidative products. Due to fuel dilution, the viscosity of the lube oil decreased over time, though the extent of dilution was lower from the B20 case. However, there is evidence that while the extent of dilution is reduced with B20, the fuel that does enter the oil is more oxidatively unstable.⁽⁹⁴⁾ Others have suggested that dilution of lube oil with biodiesel can become a problem in some cases, and attribute this to the higher boiling range of biodiesel as compared to conventional diesel.⁽²¹⁶⁾

More recently, this Indian research group investigated in-cylinder wear of medium-duty diesel engines fueled with conventional diesel and B20.⁽²⁸⁰⁾ After 100 hours of operation, the engines were disassembled and inspected. Use of B20 resulted in less deposits on cylinder parts, and lower overall wear. Wear metals were again analyzed in the used oil, and were found to be reduced in the B20 case. However, Pb and Al contents were slightly higher in lube oils from B20, possibly due to attack by FAME on paints and bearings.

In the U.S., an extensive field test was conducted using U.S. Postal Service vehicles.⁽²⁸¹⁾ After four years of operation, engines and fuel systems were removed from eight vehicles: four 1993 Ford cargo vans and four 1996 Mack tractors. For each set of four, two had been running on B20 and two on conventional diesel. All eight systems were disassembled and carefully inspected for wear and other performance attributes. With the Ford cargo vans, no significant differences were observed between the diesel and B20 cases. However, noticeable differences were observed with the Mack tractors. In particular, cylinder heads from the B20 engines contained more sludge. Additionally, over their use, the B20 engines required injector nozzle replacement, whereas the conventional engines did not. The authors commented that both of these problems could have been due to use of B20 fuel that was out of spec.

In the previously mentioned CRC study, extensive bench testing and analysis was conducted to investigate the effects of B5 and B20 on the wear and performance of fuel injection systems.^(274,275) A 500-hour injector wear test showed satisfactory performance of all fuels, except the highly oxidized B20 fuel that caused fuel filter plugging and terminated the test. Pump lubricity tests also indicated satisfactory performance with all fuels except the highly oxidized B20. Finally, a common rail test rig was built and used in a 500-hour test procedure to assess fuel performance under realistic conditions. No unusual wear was found on any of the common rail test pumps used in this study with any fuel. Overall, it appears that except for the highly-oxidized B20 fuel, the biodiesel blends exhibited satisfactory lubricity performance in all tests.

A more recent report indicates that use of B100 in light-duty indirect injection engines can lead to injector fouling, resulting in flow reductions and power loss.⁽²⁸²⁾ The extent of this problem with more advanced LD injection systems is not known, but this may be yet another reason to discourage use of biodiesel blends above B20.

6.7 Other In-Use Issues

A variety of other fuel issues are occasionally of interest with respect to in-use handling and performance of biodistillates. One example is surface tension, which can affect spray atomization, droplet size, and other functions of fuel injection.^(283,256) Although the surface tension of biodiesel is somewhat higher than that of typical No. 2 diesel fuel, this does not seem to be an important determinant in causing noticeable performance effects. Much more important is fuel viscosity, which generally correlates with surface tension, and is responsible for numerous effects as described above.

Water solubility and water contamination are other issues of some concern. At room temperature, water is very slightly soluble in conventional diesel fuel (<100 ppm), but has significant solubility in B100 (up to 1200 ppm).⁽²⁷⁷⁾ Water solubility in B20 is intermediate between these two extremes. The generally higher water levels in biodiesel can exacerbate problems with corrosion, wear, suspension of solids, and microbial growth. Due to these problems, U.S, Navy researchers have recommended that biodiesel not be used in water-compensating fuel tanks on-board marine vessels.⁽²⁸⁴⁾

The greater susceptibility of biodiesel to microbial growth also has a positive aspect, that being enhanced biodegradability in the case of spills in the environment. Because of this, biodiesel is being used in certain sensitive areas, such as wetlands and marine environments.⁽²⁰⁰⁾

When dealing with biodiesel, extra "housekeeping" precautions may be necessary to remove excess water and sediment. In particular, this is required when first introducing biodiesel into tanks previously used for conventional diesel, as accumulated water and sediment may become dispersed and plug filters under these conditions.⁽¹⁴⁾ This is true both for stationary storage tanks, and vehicle fuel tanks. NREL's Biodiesel Handling and Use Guidelines provide useful advice regarding good housekeeping with biodiesel.⁽²⁰⁰⁾

Fuel economy of biodiesel is another in-use operational issue. As already mentioned, biodiesel typically has 10% lower mass energy content than No. 2 diesel fuel (expressed as BTU/lb, or kJ/kg). However, due to its somewhat higher fuel density, the fuel economy of biodiesel expressed on a volumetric basis (i.e., miles/gallon) is only lower than that of conventional diesel by a few percent. In actual use, B20 is unlikely to result in any noticeable decrease of volumetric fuel efficiency.

Another measure of fuel efficiency is brake specific fuel consumption, meaning the amount of fuel required for the engine to perform a given amount of work. This can be expressed as either mass or volume of fuel used per bhp-hr work performed. However, due to the above-mentioned differences in energy content between biodiesel and conventional diesel, these brake-specific fuel consumption metrics can be confusing. Perhaps the best metric for comparison is energy-specific fuel consumption, meaning the energy of fuel required to perform a given amount of work (i.e., BTU of fuel/bhp-hr). On this basis, there is no significant difference between biodiesel and conventional diesel.^(283,285,256)

A final in-use operational issue with biodiesel is its effect on injection timing. Fuel is injected into a diesel engine as a consequence of a pressure wave that propagates from the fuel pump (or common rail reservoir) to the injector nozzle. The speed of this propagation is influenced by a fuel property called the bulk modulus of elasticity, which is determined by the fuel density and the speed of sound through the fuel. (Bulk modulus is the product of fuel density and the square of the sound velocity.) Compared to conventional diesel, biodiesel has slightly higher density and sound velocity. Consequently, the pressure wave propagation is slightly faster in B100, resulting in injection timing that is advanced by 1-2°.⁽²⁵⁶⁾ The consequences of this slight timing change on engine performance and emissions are unclear, with conflicting reports appearing in the literature. However, it is likely that with low concentration blends (B20 and below), any injection timing effects would be too small to be noticeable.

7. Exhaust Emissions Impacts

7.1 Background

Diesel vehicles are a significant source of both NO_x and PM emissions and, to a lesser extent, CO, HC, and other toxic species (e.g., carbonyls). Since NO_x is a precursor to ozone (O₃) formation, it is also a key variable in the development of control strategies to reduce this secondary pollutant; any increase in NO_x emissions could negatively impact ambient O₃ levels. Further, California regulations state that no fuel modification can result in an increase in regulated emissions. A potential increase in emissions could prohibit the introduction of biodistillate blends in that state. Hence, one of the key issues related to the use of biodistillates is their influence on exhaust emissions.

An earlier review of the impact of B20 on dynamometer-based emissions conducted by $EPA^{(286)}$ reported substantial decreases in HC, CO, and PM emissions, and a slight increase in NO_x emissions (see Table XIII and Fig. 26). These findings raised serious questions as to the potential impact on NO_x emissions following the introduction of biodistillate fuels. More recently, McCormick et al.⁽²⁸⁷⁾ performed an analysis using updated data and concluded that, on average, there was no net increase in NO_x emissions using B20; although the results varied greatly depending upon individual engines (Table XIII). Both studies reported significant reductions in CO, HC, and PM emissions. The discrepancy in NO_x emissions results between these studies is a critical issue that needs to be resolved. Using the extensive literature review compiled as part of this study, we address here the range of reported biodistillate emissions results to develop a better understanding of the true impacts of these fuels.

Pollutant	EPA (2002)	McCormick et al. (2006)
NO _x	+2.0	+0.6*
CO	-11.0	-17.1
HC	-21.1	-11.6
PM	-10.1	-16.4**

Table XIII. Average Percent Change in Emissions from use of B20 in HD Dynamometer Tests

*Reported as statistically insignificant. **Excludes engines equipped with DPF.

7.2 Methodology

All references compiled as part of this study were reviewed for emissions data, and the results of this task are contained in Appendix V. We identified ninety-four references reporting a total of 346 distinct emissions test results for all engines [heavy-duty (HD), light-duty (LD), and single-cylinder test engines (TE)], blends (B20, B50, B100, etc.), biodistillate sources, test cycles, control technologies, operating conditions, and model years. It should be noted that in most cases, the model year of the engine was not reported. Therefore, we chose to use the date of publication as a rough surrogate for model year. Also, the few cases using medium duty (MD) engines were lumped with the HD cases.



Figure 26. Average Emission Impacts of Biodiesel for HD Highway Engines (EPA, 2002)

In performing the analysis described in this section we chose to report the change in emissions using biodistillate vs. a reference diesel fuel (non-biodistillate fuel), rather than evaluating absolute emission rates. With this approach, we were able to more clearly identify the impacts of specific biodistillate blends on emissions. If a publication did not include a reference diesel fuel for comparison, the results were not used to evaluate a percent change in emissions; however, all emissions data, with corresponding units are shown in Appendix V. Extreme outliers were omitted from the analysis based on meeting either of the following two simple criteria:

- In studies reporting a single biodistillate and reference fuel result, did the biodistillate emissions case exceed the reference case by more than 250%?
- In studies reporting several biodistillate and reference fuel results, did the average of the biodistillate cases exceed the reference case by more than 150%?

To assess the change in emissions with respect to the blend fraction of biodistillate, the data were segregated based on engine type (HD, LD, and TE) and emission species (NO_x, HC, CO, and PM). The biodistillate results were expressed as percent difference from reference fuel. Table XIV shows the number of test points included in our analyses of biodistillate emissions, as well as the number of outlier points. As shown here, the majority of data for the HD cases were derived from B20 and B100 blends, with relatively little data from other B levels. LD and TE cases included considerably more intermediate blend levels.

Engine Class	Pollutant	B20	B100	Other Blends	Outlier Points
	NOx	24	18	8	0
	PM	22	12	5	1
	CO	22	13	6	1
HC		22	13	6	0
	NOx	10	17	30	2
	PM	3	4	8	1
LD	CO	6	9	15	1
	HC	7	10	19	1
Single	NOx	12	21	29	0
Cylinder	PM	1	1	1	0
Test	CO	8	15	19	1
Engine	HC	8	15	14	0

Table XIV. Number of Data Points used in Analysis of Biodistillate Emissions Effects

To clearly display the results of our analyses, a series of three graphs was developed for each engine type, as follows:

- 1. Data points are shown for the averages of each reported test in an individual study at a given biodistillate level. This assessment is designed to show the variability in the reported emissions test results.
- 2. Data points are shown for averages of all tests from all studies at a given biodistillate level, with error bars representing the minimum and maximum percent change. This simplifies the previous representation by collapsing the test results to a single point for each blend level.
- 3. Using the average dataset from above, a best-fit logarithmic trend line is developed for each emissions species as a function of biodistillate level. This representation is similar to what was used in the 2002 EPA document.

Given that the most commonly tested blends were B20 and B100, we focused our evaluation of the change in emissions by model year (year of publication) on these two blends. As before, a graphical analysis was employed. For each study, we plotted the percent change in emissions from the reference diesel fuel based on the publication year. Each data point represented an average reported emissions level from a given study. Included in this analysis are the results for all engines, operating conditions, and biodistillate types. A different symbol is used to distinguish the few renewable diesel fuel cases from the majority biodiesel fuel cases. The data were further sorted by engine class (HD, LD, and TE), NOx emission control system (yes or no), and test procedure (engine dynamometer and chassis dynamometer). It should be noted that there was no differentiation among biodistillate feedstock type (i.e. soybean, rapeseed, algae, etc.) or among operating conditions.

7.3 Impact of Biodistillate Blend Level on Criteria Emissions

To evaluate the impact of biodistillate blend level on criteria emissions, a total of nine graphical analyses were generated as follows:

- Three engine classes: HD, LD, TE, with each chart containing data for NO_x, CO, HC, and PM.
- Three representations of the emissions data:
 - Individual test results vs. blend level
 - Average of all test results at a given blend level vs. blend level
 - Logarithmic fit of the average of all test results at a given blend level vs. blend level

This approach was designed to show the wide range of results, while providing an increasing level of clarity by which the observations could be interpreted. Although the results have been segregated by engine class, within each engine class the reported observations are for all biodistillate sources, test cycles, control technologies, operating conditions, and model years.

The three representations for HD, LD, and TE are presented in Figures 27, 28, and 29, respectively. Each graph displays the percent change from a reference diesel fuel with respect to biodistillate percentage. The top panel in each figure contains a data point for the average of each individual test result (i.e., studies generally reported a range of emission rates for a given engine and fuel) at a given biodistillate level and is color coded by pollutant (NO_x, CO, PM and HC). To display the full range of observations, the y-axis spans a percent change of +/- 100%. A linear trend line for each of the species is included, which provides an assessment of the overall change in emissions with increasing levels of biodistillate.

The middle panel collapses the data from the top panel by displaying the average of all test results at a given blend level vs. blend level. Error bars represent the minimum and maximum percent change from a reference diesel fuel for all test results at a specific biodistillate blend level. (These data points and error bars are offset slightly along the x-axis to provide better graphical clarity.) Again, they are color coded based on the four pollutants and a linear trendline is displayed for each of the species.

The bottom panel in each figure uses the same dataset as the middle panel, but displays a logarithmic trend line based on the average of all emissions for a given biodistillate level. (Note that for this case, the range in the y-axis is from +20% to -40%.) This is the simplest way of showing the trend in emissions for each pollutant as a function of biodistillate level, and allows for better comparison with the trends reported in previous reviews.

For all three approaches, trendlines were extrapolated beyond the data set to a B5 level, but were not force fit through zero (i.e., 0 % change for 0 % biodistillate). The location of the trendline at the lowest biodistillate levels should be treated with caution. This is especially true for the logarithmic result, where both the magnitude and direction of the trendline is primarily determined by the lowest % biodistillate data points. A thorough statistical analysis of these data was beyond the scope of our study.



Figure 27. Effects of Biodistillate Blends on Exhaust Emissions from HD Engines



Figure 28. Effects of Biodistillate Blends on Exhaust Emissions from LD Engines



Figure 29. Effects of Biodistillate Blends on Exhaust Emissions from TE
Using the information presented in Figures 27-29, we can draw a number of conclusions regarding the potential impacts of biodistillate blend levels on emissions, with the caveat that this approach does not allow for the assessment of the impacts of specific biodistillate sources, test cycles, control technologies, operating conditions, and model years. A further limitation of this approach is that by not evaluating specific biodistillate sources, a linkage between biodistillate fuel properties and emissions cannot be determined. Given these limitations, we make the following observations regarding emissions effects of biodistillate fuels:

- Heavy-duty engines (including medium-duty):
 - NO_x emissions differ very little from reference diesel fuel. The effects at B20 and below are indistinguishable from zero. A slight NOx increase (2-3%) may occur with B100.
 - CO, HC, and PM are decreased for all B levels, and decrease further with increasing % B.
 - There is a greater impact of % B on HC and PM than on NO_x and CO.
- Light-duty engines:
 - NO_x emissions are elevated for all B levels, and increase slightly with increasing % B.
 - The magnitude of the NO_x increase is greater than for the HD case.
 - CO, HC, and PM decrease for all B levels, but there is less of an impact of % B on emissions than for HD engines.
 - There is a greater impact of %B on HC and PM than on CO.
- Single cylinder test engines:
 - All emission species decrease with use of biodistillate at all blend levels.
 - NO_x emissions increase slightly with increasing % B.
 - CO and HC emissions are relatively flat and do not appear to be greatly influenced by % B.
 - PM emissions decrease with increasing % B.

The overall appearance of these trend lines is quite similar across all three engine types, exhibiting elevated NO_x emissions and reduced CO, HC, and PM emissions with increasing biodistillate content. However, the magnitude of the effects varied somewhat from one engine type to the next. In most cases, the PM effect appeared to be the strongest, while the NOx effect was weakest. The range of effects among the four pollutant species was narrower with the TE cases. The reasons for this are unknown, but may be due to greater control over engine operating parameters and greater reliance on steady-state conditions (i.e., fewer transients).

To compare the results of our analyses with the findings of other studies, the regression equations derived from the logarithmic trendlines were used to predict the % change in emissions of a given pollutant for a specified % B. These regression equations (shown below in Table XV) were determined for two different data sets:

- (1) Full data set: included results from both biodiesel and renewable diesel fuels
- (2) Partial data set: included only results from biodiesel fuels. This data set was slightly smaller, with 0-3 data points eliminated, depending upon the engine type and pollutant species investigated.

	Pollutant	HD	LD	TE
Full Data	NO _x	y=1.693*Ln(x) - 5.337	y=2.803*Ln(x) + 2.413	y=3.971*Ln(x) - 20.017
Set	CO	y=-2.237*Ln(x) - 9.927	y=-1.371*Ln(x) - 5.987	y=-1.768*Ln(x) - 8.063
Renewable	HC	y=-11.192*Ln(x) + 14.299	y=-3.927*Ln(x) - 4.829	y=-0.552*Ln(x) - 13.722
Diesel)	PM	y=-13.233*Ln(x) + 24.118	y=-10.635*Ln(x) + 17.304	y=-11.313*Ln(x) + 20.027
Partial Data Set (Biodiesel Only)	NO _x	y = 2.259*Ln(x) - 7.410	y = 2.803*Ln(x) + 2.413	y = 3.971Ln(x) - 20.017
	CO	y = -2.799*Ln(x) - 10.306	y = -1.122*Ln(x) - 6.987	y = -1.768*Ln(x) - 8.063
	HC	y = -11.962*Ln(x) + 14.672	y = -3.161*Ln(x) - 7.921	y = -0.552*Ln(x) - 13.722
	PM	y = -11.236*Ln(x) + 9.547	y = -11.313*Ln(x) + 20.027	y = -8.618*Ln(x) + 12.930

Table XV. Regression Equations Derived from the Logarithmic Fits Presented in Figs. 27-29 (where x is the % biodistillate and y is the predicted change in emissions)

Using the equations provided in Table XV, changes in emissions for a given biodistillate blend level can be predicted. The results for both B20 and B100 are presented below in Table XVI.

Table XVI. Predicted Changes in Emissions using B20 and B100

	Dollutant	Full Data Set			Biodiesel Only Data Set		
	Fonutant	HD	LD	TE	HD	LD	TE
B20	NO _x	-0.3	+10.8	-8.1	-0.6	+10.8	-8.1
	CO	-16.6	-10.1	-13.4	-18.7	-10.4	-13.4
	HC	-19.2	-16.6	-15.4	-21.2	-17.4	-15.4
	PM	-15.5	-14.6	-12.9	-24.1	-13.9	-12.9
B100	NO _x	+2.5	+15.3	-1.7	+3.0	+15.3	-1.7
	CO	-20.2	-12.3	-16.2	-23.2	-12.2	-16.2
	HC	-37.2	-22.9	-16.3	-40.4	-22.5	-16.3
	PM	-36.8	-31.7	-26.8	-42.2	-32.1	-26.8

(based on the regression equations shown in Table XV)

Notes: HD = heavy-duty and medium-duty CI engines

LD = light-duty CI engines

TE = single cylinder CI test engines

Going from B20 to B100 reduced emissions of CO, HC, and PM for all three engine types. NOx results are less clear. Our assessment of HD NOx results suggests that biodistillates have no effect at low levels (B20), but increase NOx slightly (2-3%) at B100 levels. LD results suggest a more consistent NOx increase of 10-15% for B20 and B100, respectively, though the high variability in these emissions results (see Fig. 28) makes these conclusions questionable. For the single cylinder TE cases, NOx emissions appear to be reduced slightly at a B20 level, but not at a B100 level.

As a check on the analyses reported in this section, we can compare our HD results against those of EPA (2000) and McCormick et al. (2006) that were shown in Table XIII. The comparison of B20 emissions findings from those studies and this study are summarized in Table XVII. Overall, the predictions for all species are quite similar. Based on these findings, we conclude that the use of biodistillate blends at a 20% level has a positive impact on diesel CO, HC, and PM emissions, with little impact on NO_x emissions. Perhaps the most valid conclusion regarding NOx is that offered in a recent NREL report, "...examination of the NOx results shows that the effects of biodiesel can vary with engine design,

calibration, and test cycle. At this time, the data are insufficient for users to conclude anything about the average effects of B20 on NOx, other than it is likely very close to zero."⁽²⁰⁰⁾

Pollutant	EPA, 2002	McCormick et al., 2006	This Study	
			Full Data	Biodiesel Only
NO _x	+2.0	+0.6*	-0.3	-0.6
CO	-11.0	-17.1	-16.6	-18.7
HC	-21.1	-11.6	-19.2	-21.2
PM	-10.1	-16.4**	-15.5	-24.1

Table XVII. Comparison of Average Change in Emissions from HD Dynamometer Tests using B20

*Reported as statistically insignificant.

**Excludes engines equipped with DPF.

We can also compare the HD results for all blend levels reported in this study with the EPA (2002) findings that were shown in Fig. 26. Overlaying the data from Fig. 27 (bottom panel) with those of Fig. 26 yields the chart shown in Fig. 30. The solid lines represent the findings from this work, while the dashed lines present the EPA (2002) findings. It is important to remember these data represent a compendium of engines and control technologies, model years, biodistillate sources, and test cycles, with the EPA (2002) observations reflecting an older set of experiments and engines. Given this caveat, the findings are similar, with NO_x emissions increasing and CO, HC, and PM emissions decreasing for all blend levels; although the percent change in emissions for all pollutants is lower for this study than in the previous report. One possible explanation for this discrepancy is that emissions from newer engines (and more advanced control technologies) compiled as part of this study are lower overall, leading to a reduced impact from the introduction of biodistillate blends.



Figure 30. Comparison of the HD Engine Results from this Study with EPA (2002) ⁽²⁸⁶⁾

7.4 Influence of Model Year on Emissions

One possible influence on the change in emissions following introduction of biodistillate fuels is the model year of the engine, and as a consequence, the engine technology. Newer engines, with improved emissions control systems and lower overall exhaust emissions could affect the observed impacts of biodistillates. Using the emissions data contained in Appendix V, and the year of publication as a surrogate for model year, we used a similar graphical analysis technique as previously described to evaluate potential emissions trends with model year.

Two graphs for each pollutant were created; one for B20, the other for B100. Each emissions test was represented by a data point for the average change in emissions reported in the published study. Error bars represent the minimum and maximum reported values. The data were further sorted by engine size (HD, LD or TE), NOx emissions control system (yes/no = dotted/solid error bars), and testing procedure (engine or chassis dynamometer test). This approach provides easy observation of variability in the reported data, with the caveat that there is no differentiation among biodistillate type (i.e. soybean, rapeseed, algae, etc.), test cycles, or operating conditions.

The graphs of % change in emissions at fixed biodistillate levels (B20 and B100) for a given year of publication (surrogate for model year/technology) are shown in Figs. 31-34. (For improved graphical clarity, the data points and error bars are offset slightly along the x-axis.) Given the limited results for each year, coupled with large error bars associated with most data points, it is difficult to draw quantitative conclusions. However, qualitatively it appears that the % change in all emissions (for both B20 and B100) is largely unaffected by model year/technology. The only case where there may be a discernable trend is a decrease in PM when using B100 in newer vehicles.

Figures 31-34 also include data points for renewable diesel fuel, shown by open symbols. At the present time, there are very few published reports of emissions effects of renewable diesel fuels – only 4 points are included in the B20 plots, and a single point in the B100 plots. Based upon such scant information, it is not possible to draw definitive conclusions. However, it appears that the emissions effects of renewable diesel fuels are largely similar to those of biodiesel fuels.



Figure 31. NO_x Emissions for Biodistillate Fuels Compared to Reference Diesel Fuel



Figure 32. CO Emissions for Biodistillate Fuels Compared to Reference Diesel Fuel



Figure 33. HC Emissions for Biodistillate Fuels Compared to Reference Diesel Fuel



Figure 34. PM Emissions for Biodistillate Fuels Compared to Reference Diesel Fuel

7.5 Impact of Blend Level on Carbonyl Emissions

Another question associated with use of biodistillate blends is the potential impact on emissions of toxic species. To address this issue, we reviewed the database for emissions data beyond the criteria species of NO_x , CO, HC, and PM. The findings were limited, with most observations being for carbonyls. A total of seven papers contained information on the change in emissions compared with a reference diesel fuel. While some of the papers contained results for speciated carbonyls, a number only reported total carbonyl emissions.

These results for the major species (formaldehyde and acetaldehyde) and total carbonyls are contained in Appendix V-2 and presented graphically in Figure 35. The previously described methodology to evaluate emissions was also applied in this case. Due to the limited number of data points, Figure 35 contains the results for both HD and LD engines, along with a logarithmic fit to the complete data set. Overall, the results imply there is a decrease in emissions with increasing blend level; although a number of studies reported increasing emissions for B20. This conclusion is somewhat surprising since biodiesel, which consists of oxygenated species (FAME), might be expected to increase aldehyde emissions. On the other hand, carbonyl formation from esters is not expected to be as facile as from alcohol fuels or ethers (such as MTBE).



Figure 35. Effects of Biodistillate Blends on Carbonyl Exhaust Emissions (Both HD and LD engines)

7.6 Emissions Reduction via Oxygenate Blending

To address potential NOx emissions problems resulting from use of biodiesel, many researchers and organizations have investigated approaches involving the blending of additional oxygenated components. Use of fuel/water emulsions is one such approach. In one of the earliest reports, straight vegetable oils were emulsified with 5-10% water and the combustion performance was examined in the laboratory.⁽²⁸⁸⁾ Evidence of "explosive combustion" of the oil-water emulsion droplets was obtained, and simultaneous reduction of NOx and PM emissions was demonstrated.

More recently, academic researchers from Taiwan reported on emulsification of soy-derived biodiesel with water.^(289,290) Various emulsion formulations were investigated, including 2-phase water/oil (W/O) and 3-phase oil/water/oil (O/W/O) blends, having total water concentrations of about 10%. It is noteworthy that the viscosity of these emulsions was considerably higher than that of neat biodiesel – by almost a factor of two. Emissions results using an engine dynamometer test stand showed small, but significant reductions in NOx with all the emulsion blends. The greatest NOx reduction was obtained using an emulsion that included aqueous ammonia.

In another recent study, researchers from Oak Ridge National Laboratory tested a soy-derived biodiesel and a 10% water emulsion in a 4-cylinder light-duty diesel engine.⁽²⁹¹⁾ This work showed that the NOx increase in using B100 compared to ULSD could be completely offset by use of the biodiesel/water emulsion. The emulsion fuel also reduced PM emissions significantly when EGR was used, but not without use of EGR.

Fuel blends of ethanol with biodiesel have also been explored. This could be especially relevant to biodiesel composed of FAEE, where excess ethanol remains in the product mixture.⁽²⁹²⁾ However, addition of ethanol has a critical effect upon the fuel's vapor pressure, with very low ethanol concentrations resulting in dramatic increases in vapor pressure, along with a significant decrease in flash point. Thus, ethanol blends (with both conventional diesel and biodiesel) introduce safety concerns regarding handling of the blends.

Blends of conventional diesel fuel with ethanol are sometimes referred to as "diesohol." Besides the problems of vapor pressure and flash point mentioned above, diesohol blends are often unstable with respect to phase separation, particularly when contaminated with low concentrations of water.⁽²⁹³⁾ It has been reported that including biodiesel as an additional blending component improves the stability of diesohol. In one case, a blend of 80% diesel, 15% biodiesel, and 5% water was reported to give optimum performance, though no NOx emissions reductions were observed with this blend.⁽²⁹⁴⁾

This same approach of using biodiesel to stabilize diesohol may be employed with the commercial product called $O_2Diesel^{TM}$. This material is reported to consist mainly of conventional diesel fuel, with 7.7% ethanol and a small amount of proprietary "fatty acid-based stabilizer additive."⁽²⁹⁵⁾ $O_2Diesel^{TM}$ has been shown to reduce NOx slightly (about 2%) and PM more substantially (about 20%) compared to conventional diesel fuel. However, due to the flammability concerns resulting from its high vapor pressure and low flash point, special precautions are required for storing and using $O_2Diesel^{TM}$. In particular, its use is limited to centrally-fueled fleets, where both the vehicles' fuel tanks and the refueling storage tanks are equipped with flame arrestors.

Various other oxygenates have been blended with biodiesel in an effort to improve emissions. For example, Japanese researchers have investigated blends of dimethyl ether (DME) in biodiesel produced from palm oil and used cooking oil.⁽²⁹⁶⁾ Benefits reported include reduced viscosity and pour point of the fuels, slight NOx reductions, and substantial reductions in smoke levels. Nothing was stated about the flash point of DME/biodiesel blends, but this surely would be a matter of concern if used commercially. Similar benefits have been reported for blends of diethyl ether (DEE) with biodiesel.⁽²⁹⁷⁾

In a very recent report, blends of conventional diesel and biodiesel were emulsified with a "biosolution" consisting of 96.5% organic enzyme and 3.5% water.⁽²⁹⁸⁾ Emissions of PM and PAH were reduced when using these emulsion fuels, but NOx emissions were not measured.

8. Life-Cycle Analysis and Land Use Impacts

In comparing energy and environmental impacts of different fuels, it is increasingly recognized that the entire life-cycle of the fuel must be considered. In fact, life-cycle models have become a common aid for policy regarding the use of alternative fuels. ^(4,15,22,299,300) Life-cycle assessments (LCA) provide a tool to evaluate the "cradle-to-grave" energy and environmental impacts that result from all stages of a product's life, from manufacturing through disposal. These environmental impacts can include energy use, emissions produced, water consumption, eutrophication and acidification potential, and other factors. According to a recent EPA report,⁽³⁰¹⁾ there are three steps involved in conducting an LCA to assess these energy and environmental impacts:

- 1. Compiling an inventory of relevant inputs and outputs of a process stream
- 2. Evaluating the potential impacts associated with the inputs and outputs
- 3. Interpreting the results to make informed decisions

A full-fuel LCA starts with raw material extraction and ends with fuel consumption.⁽³⁰²⁾ For a biofuel, this includes all inputs and requirements for feedstock growth, harvesting, fuel production, distribution and combustion as well as intermediate transportation steps. Fig. 36 shows a typical pathway for biodiesel production from soybeans.





Life-cycles of biofuels are data-intensive, requiring specific inputs for fertilizer use, harvest yields, electricity mixes, processing efficiencies, and many other factors. Clearly defined boundaries are crucial for calculating robust LCA results. Data used is often specific for a particular feedstock or process and may also be regionally specific, although some databases use averages for a larger region.^(303,304,305,306,307) Because of variations in pathway boundaries and assumptions among studies, LCA results are best used for comparison of energy use and emissions relative to conventional petroleum fuels and other products within the study itself, and not for direct comparisons among different studies.⁽³⁰³⁾

LCA are frequently used to assess the relative attractiveness of various transportation fuels, and are becoming a common aid in determining the most desirable options for sustainable fuel and energy processes. Numerous LCAs have been conducted for ethanol fuels; by comparison, the LCA literature on

biodiesels is scant. A literature review we undertook for biodistillate LCA studies considered approximately 40 publications. These studies are discussed below in further detail, with emphasis given to results for energy return and GHG emissions.

8.1 Fuel LCA Overview

Full-fuel LCAs generally take into account all energy flows and emissions associated with production of the final energy source in its consumable form. These steps can be broken into two parts: well-to-tank (WTT) and tank-to-wheels (TTW). The combination of the two parts represents the complete well-to wheels (WTW), or cradle-to-grave, life-cycle for a transportation fuel.

The WTT pathway for a biodistillate fuel commonly includes growth of the crop which may involve landuse change (LUC) and farming inputs like fertilizers, harvesting of the crop, processing or crushing to extract the oil, production (via transesterification or some other method), and distribution to the fueling station. This also includes any intermediate transportation steps. The TTW analysis includes combustion of the fuel in a vehicle, and depends on the type of vehicle, its efficiencies and type of driving. Common LCA practice for biofuels is to include only fossil carbon inputs. Thus, non-fossil carbon emitted during combustion of a biofuel is ignored (or offset) in the TTW portion of the life-cycle. (This is sometimes referred to as the "carbon neutral principal," since the carbon being emitted is the same carbon that was recently absorbed by the plant during its growth through photosynthesis.⁽³⁴⁾) Therefore, there is minimal net contribution to GHG emissions from combustion of biofuels, though NOx and other minor pollutants do contribute to a small degree. Because the TTW portion of most biofuels' life cycle is so small, the WTT results for GHG emissions are generally similar to the complete WTW results.

8.1.1 LCA Modeling Tools

The complete WTW pathway of a biofuel is extremely data-intensive. However, there are numerous existing LCA modeling tools and other databases that can be used, many of which are available in the public domain. Existing models usually include a specific pathway with a given set of default assumptions that may or may not be changed by the user. Several private companies have also developed their own LCA models to aid in their decision making. ST&T2 Consultants recently performed a review of existing LCA tools, and found approximately 37 models.⁽³⁰³⁾ Of those 37, the ten listed in Table XVIII are applicable for biofuels. However, pathways for biodiesel are quite limited in these models, as described below.

The GREET model is one of the most comprehensive LCA tools available in the public domain, and includes over 100 fuel production pathways and more than 70 vehicle/fuel systems. The GREET model is used as an aid for policy decisions in the US. In fact, California is developing its own California GREET model (CaGREET) with boundaries, pathways, and transportation distances specific to fuel production and use in California.⁽³⁰⁸⁾ Similarly, GHGenius is used for Canadian policy. Many of these publicly available models include default assumptions for energy mixes and transportation distances that minimize differences between models. However, the default assumptions can be adjusted with more site-specific details for individual analysis.

This list of models is not exhaustive; it does not include many LCA models that do not have biodiesel pathways. Additionally, many companies conduct LCAs independently of these modeling tools. Several databases also exist in the public domain to support fuel LCAs. Some agencies, including NREL and EcoInvent, have made their databases publicly available.^(304,305)

	Biodiesel		Publicly	
Model	Pathways	Region	Available	Notes
BEES	None	US and EU data	Yes	Adapted for bio-based
				products
BESS	None	US	Yes	Specific for corn-to-
				ethanol
EBAMM	None	US data	Yes	Excel model uses data
				from 9 difference studies
				and outcomes from each
				dataset
EIO-LCA	None	US and EU data	Yes	
GaBi	None	EU (Germany)	Yes - \$\$	Can model ethanol
GEMIS	From forest residue	EU data	Yes	Limited pathways.
GHGenius	From soybeans,	US and Canadian	Yes	200 pathways. Used in
	canola, palm, tallow,	Data		Canadian policy decision
	yellow grease and			making.
	marine oils.			
GREET	Soybeans	US Data	Yes	100 pathways, used in
				US policy.
LEM	Soybeans	US data	No	Basis of GHGenius.
SimaPro	None	EU and US data.	Yes - \$\$	Has biodiesel
				processes, but no
				pathways.

Table XVIII. LCA Tools for Transportation Fuels (Taken from References^(303,309))

8.1.2 Variations in Modeling

Although established databases and modeling tools exist, differences in LCA modeling approaches are still common. Two models can be run with the same types of assumptions and produce very different results.⁽³¹⁰⁾ However, standards have been implemented to maintain consistency in data. ISO 14044:2006 provides modeling requirements and guidelines, and ISO 14048:2002 outlines standards for data documentation and format within the model.^(311,312) However, the standards do not specify methodologies that should be used, so results of different assessments can be highly varied. Therefore, fuel LCA models are typically used to determine the relative benefits of different scenarios in which conventional petroleum fuels are displaced with alternative fuels.

Differences in methodologies arise from variations in defining fuel pathways, scenario boundaries, input assumptions, and dealing with co-products. Most LCA data inputs are specific to the process, fuel type, or region that is being evaluated. For example, crop yields can vary dramatically based upon type of crop or growing location; also, energy use for a 2nd Generation production process may not be well established and must be estimated from scant data. Generally, LCA inputs and assumptions represent reported industry-wide averages.^(313,307,314) However, some data may come from literature rather than process technology, especially in cases of new technology.

The quality of input data clearly affects LCA results for biofuels. As defined by Wang,⁽³¹⁵⁾ some of the key issues (several of which are discussed below) include the following:

- land use changes
- nitrogen fertilizer for plant growth
- conversion factor of nitrogen fertilizer to N₂O
- crop yields

- other farming energy and chemical requirements
- energy use in biofuel processing plants -- including the type and amount of process fuel
- credits given to co-products
- scale of production

8.1.2.1 Land-Use Change

The demand for additional crops to support a biofuels industry could result in creation of new agricultural regions, as well as conversion of existing agricultural lands to new uses. This topic of land use change (LUC) and the way that it is considered (or not considered) in LCA modeling has drawn considerable attention, partly due to recent publications by Searchinger et al. ⁽³¹⁶⁾ Fargione et al. ⁽³¹⁷⁾ and Crutzen et al. ⁽³¹⁸⁾ Both direct and indirect LUC may have significant impacts on the overall life-cycle of a fuel. Direct impacts are those that are associated directly with the cultivation of feedstocks used to produce a biofuel in the region where it is used. Indirect effects are those that could potentially arise when a crop is produced in one region of the world in response to fuel demand in another region.

Most LCA models include some type of direct LUC assessment to address changes in GHG emissions resulting from modifications to soil carbon, or variations in above ground biomass from preparation of existing crop-lands or conversion to new crop-land.⁽³⁰³⁾ Methods of including direct LUC are somewhat controversial, specifically with respect to biologically-produced N₂O emissions.⁽³¹⁸⁾ The IPCC consensus is that N₂O has a global warming potential (GWP) 296 times that of CO₂, so small changes in N₂O can result in significant differences in GWP.⁽³¹⁹⁾ Therefore, it is crucial to account for all N inputs and outputs from cultivation of land to grow biomass -- including crop residues, fertilizer, N fixation, manure, deposition, gaseous losses, crop output, runoff, N transfer between co-rotated crops, and others. It is also important to know how these factors change over time.⁽³²⁰⁾ Variations in assumptions about N₂O can swing the final GWP results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

The IPCC recommends use of an N₂O conversion factor for LCA modeling to estimate the amount of N₂O emitted per gram of Nitrogen fertilizer input. This factor has a significant impact on the overall GHG emissions during the agricultural stage of a biodistillate's life-cycle, but its value is very controversial. Many models use the IPCC-recommended factor of 1.325%, or something similar. The GREET model uses the IPCC value⁽³¹⁵⁾ and the GHGenius model uses a factor of 1.125%.⁽³⁰³⁾ Using these relatively low conversion factors generally results in favorable life-cycle GHG emissions for biodiesel relative to conventional diesel. However, Crutzen et al.⁽³¹⁸⁾ concluded that the IPCC emissions factor of 2.24-3.74.⁽³¹⁵⁾ This change results in biodiesel having increased life-cycle GHG emissions relative to conventional diesel. Delucchi's LEM model, which includes a more complete Nitrogen balance than other models, shows a 50% increase in life-cycle GHG emissions for biodiesel relative to petroleum diesel, largely because of N₂O impacts.^(321,320,322)

Indirect LUC has been a topic of recent publicity and concern as having potentially serious adverse GHG impacts. Searchinger's paper discusses the possibility that as crops are diverted to produce more fuels in one geographic location, increased crop production will be required elsewhere to compensate. This increased production could occur through displacement of existing crops, expansion of croplands, or intensification of existing production -- though economic equilibrium only occurs for expansion or intensification.⁽³¹⁰⁾ Expansion of croplands may require reducing forest lands or other fallow lands elsewhere, which could result in an extremely large release of CO₂ previously sequestered by roots and soil. Intensification of production may require more fertilizer usage. Both could have a net-negative GHG effect on the biofuel's life-cycle.

Many LCA models do not include the effects of indirect LUC because they are much more difficult to analyze and require subjective assumptions that contain substantial uncertainty. However, policy is trending toward including indirect LUC into already required LCA models.⁽³²³⁾ To do this, some type of economic model is required to estimate the economic supply and demand of developing new crop lands. The California Air Resources Board is working to link its CaGREET model with the GTAP Model (Global Trade Analysis Project, from Purdue University), in an effort to include the effects of indirect LUC. Other models being utilized include FASOM (Forest and Agricultural Sector Optimization Model from Texas A&M University), and FAPRI (Food and Agricultural Policy Research Institute at Iowa State University).⁽³²³⁾

8.1.2.2 Method of Dealing with Co-products

Several by-products are also produced during the manufacturing of biodiesel; for example, animal feed meal is produced during the oil extraction process, and glycerin is produced during transesterification. Other co-products such as naphtha or propane may be produced in renewable diesel manufacturing involving catalytic hydroprocessing.⁽¹⁷⁸⁾ Common practice in LCA modeling is to allocate some of the energy and emissions produced during the fuel life-cycle to these co-products since they can replace other similar products in the market. Several different methods of allocation are commonly used.^(324,325,326) These are described below in more detail.

- *Physical Allocation*—Environmental impacts are allocated to each by-product and the biofuel based upon a common physical parameter such as mass (kg) or energy (MJ). A drawback of this method is that it does not consider the actual environmental impacts that have been offset by replacing other products. The physical allocation method simply assumes that all forms of mass or energy are of equal value.
- *Economic Allocation*—Calculations are performed on the basis of the economic value of the biofuel and other valuable by-products. The economic allocation method has similar drawbacks to the physical allocation method in that it does not consider actual changes to environmental impacts from replacement of other materials.
- *Expanded Allocation (Displacement or Substitution Method)*—By-products are assumed to replace existing products. The environmental impacts from the replaced product are subtracted from the emissions and energy needed to produce the biodiesel. Changes in assumptions, however, can have significant effects on the results. Additionally, the expanded allocation method does not make corrections for changes in scale. This could be a problem for large-scale production, for example, once the glycerin market becomes saturated.
- *No Co-Product Allocation*—All energy and emissions incurred in the lifecycle are attributed to the final biofuel product. While perhaps the easiest approach to use, failing to allocate any energy or environmental impacts to co-products is clearly an over-simplification of reality.

The choice of allocation method may significantly affect the final results of the LCA. Several studies included in the literature review examined the effects that different allocation methods have on the results. Bernesson, et al. studied the effects of all four allocation methods listed above, as well as a range of production plant sizes. ⁽³²⁴⁾ They found that differences in plant size were almost negligible in some cases, but the allocation method had significant impacts, reducing GWP by a factor of 2 to 3 compared to no allocation, and possibly resulting in the process becoming a net-supplier of energy for the expanded allocation methods could result in up to a 250-fold difference in extreme cases. ⁽³²⁶⁾ Numerous other studies included cases for one allocation method compared to no allocation, which generally produced large differences in LCA results.

The allocation of by-products is also controversial; the choice of methods is not clearly defined, but has a large effect on the LCA results. For example, many studies give glycerin a by-product credit; however, in some regions, the glycerin market may already be saturated from the soap making industry, which is not expected to change as biofuel production is increased. In the EU, a 5% replacement of diesel fuel with biodiesel would result in 1.5 MMT of additional glycerin. ⁽³⁰⁷⁾ Since this market already appears to be saturated, it would not be able to accommodate extra glycerin. To legitimately allocate energy or emissions to the by-product, another market must be identified. Definition and boundaries of allocation methods need to be more clearly defined to make meaningful comparisons between different LCA studies.

8.2 Biodiesel LCA Literature Review and Results

A literature review of LCA studies of biodiesel pathways was conducted. The review considered approximately 40 published papers and reports covering a broad range of feedstocks and methods of production. Some studies compared biodiesel to conventional diesel while others looked at only a single fuel, but investigated differences in assumptions, processes, or life-cycle scenarios. The most common feedstocks were rapeseed (in many EU studies) and soybeans (in many U.S. studies). Most studies considered biodiesel production via transesterification with methanol, though a few also investigated renewable diesel produced via catalytic hydroprocessing. Each paper is identified and briefly summarized in Appendix VI-1 and VI-2.

To compare the differences in the results among these published studies, the environmental impacts are shown both on an absolute basis and relative to the reference fuel used. Both the energy and CO_2 equivalent emissions are discussed further.

8.2.1 Energy

The life-cycle energy inputs required to produce and deliver a unit of fuel is one of the impacts most frequently assessed in an LCA. The overall energy benefit or energy return (ER) of the entire process is determined by dividing the energy out of the process (the heating value of the fuel) by the total life-cycle energy inputs. A net energy benefit results when the ER is greater than one; an ER less than one indicates more energy is required to produce the fuel than is contained in the final product. [This value of ER is sometimes called Energy Return on Investment (EROI).] Common practice in biofuel LCA is to include only fossil energy inputs in the ER calculation, but not any renewable energy inputs, such as the energy content of the plant itself. This typically results in an ER greater than one for biodistillates. In contrast, the energy requirements to make conventional diesel are almost entirely fossil energy, (including the energy content of petroleum itself) which typically results in a life-cycle ER of less than one.

[In addition to total ER, some studies explore the nature of the energy sources used in the biofuels' lifecycle, particularly the use of petroleum. For certain policy purposes, it may be desirable to reduce petroleum use, even though this could result in greater use of coal (or other fossil fuels) and lower overall ER. These policy issues regarding petroleum reduction are not addressed in this review.]

Of the 42 studies examined in our literature review, 20 reported an ER value -- or something equivalent. Fig. 37 shows the ranges of ER results from each. A single point in the figure depicts a study in which a single result was reported; vertical bars represent the minimum and maximum of a range of values reported. In some cases, the range represents the high and low values for a single scenario; in other cases, the range encompasses values for numerous scenarios in a particular study. The numbering refers to the study numbers provided in Appendix VI-1 for each reference, which provides a more detailed summary of results for each paper.

Energy Return



Figure 37. Energy Return for 19 LCA Models (Study Nos. provided in Appendix VI-1 and VI -2)

Note that the x-axis in Fig. 37 (and subsequent figures) is a time line, representing the year in which the study was published. Also, note the break in the x-axis after the first study in 1998. Additional spacing along the x-axis was used to avoid overlapping of data points – see for example the three results shown for Study No. 6 in the year 2003. Also note that different symbol shapes and colors are used to distinguish biodiesel life-cycle cases from renewable diesel cases, and different colors represent different feedstocks.

Several studies compared the biodiesel ER to a reference fuel (typically conventional diesel), which is shown in Fig. 37 as dark gray circles. (In a few cases, the reference fuel was some other alternative fuel such as ethanol, which is not shown here). The shaded horizontal band in Fig. 37 represents the range of ER reported for petroleum diesel. (A few results were excluded from this designated range because of reporting differences or unrealistic values ⁽³²⁷⁾.) In nearly every case, the life-cycle ER for petroleum diesel was below one, and the life-cycle ER for biodistillate fuels was above one.

Figure 37 clearly illustrates the variability in results among different studies, whether for traditional methods of production (biodiesel via transesterification) or 2^{nd} Generation methods (renewable diesel via hydroprocessing or gasification). Although the results are quite diverse, generally a net energy benefit (ER>1) for biodiesel is shown. The mean value reported is 3.1, with most cases falling below an ER value of 4. Of the few studies reporting larger ER values, one (Study No. 24) is for hydroprocessing vegetable oil using the UOP EcofiningTM process. ⁽¹⁷⁸⁾ Study No. $41^{(328)}$ is also for the UOP EcofiningTM process, but only when tallow is used as a feedstock is the ER greater than 4 (for both EcofiningTM and transesterification.) The differences between these two studies will be discussed in more detail in the next section on critical references.

Study No. 28 is the only LCA reported for Jatropha.⁽³²⁹⁾ The variability of results is extremely large due to a wide range of sensitivity analyses for both best and worst cases, but the mean ER of all scenarios is about 4.8. Study No. 22 reports a high and low value for transesterification of rapeseed based on

allocation of co-products or no allocation for specific use on an organic farm.⁽³³⁰⁾ The assumptions used in this paper are specific to the farm and its proximity to a production plant, which results in the higher estimates. Study No. 10 shows a broad range of ER values due to a variety of calculation approaches. This study has been identified as a critical study and will be discussed in more detail in the next section.⁽³⁰²⁾

Many of the studies were completed within the EU, and make comparisons between rapeseed and sunflower oil as a feedstock. However, even these results are not consistent. Studies numbered 6, 16, 18, and 38 (Venturi,⁽³³¹⁾ Cocco,⁽³³²⁾ Edwards,⁽³⁰⁷⁾ and Prieur,⁽³³³⁾ respectively) all compared rapeseed and sunflower within specific regions in the EU. Study Nos. 6 and 16 were both within Italy, No. 38 was for French conditions, and No. 18 was a broad study for average EU 25 conditions. Although the three studies for specific countries showed rapeseed to have a slight advantage over sunflower, the average EU conditions showed the opposite. Similar inconsistencies are reported throughout the literature. Several critical studies will be discussed in more detail to help identify the reasons for these differences.

8.2.1.1 Critical LCA Studies for Energy

Some of the 42 studies we evaluated were identified as critical based on the frequency of citation in other studies, the quality of the assumptions, the number of scenarios studied, and the robustness of the results. A brief description of the energy results of each of these critical studies is given below.

Study No. 1 was reported by NREL in 1998.⁽³¹⁴⁾ This is a frequently cited study, and is considered one of the most authoritative references for biodiesel LCAs in the U.S. It compares the environmental impacts of biodiesel with those of petroleum diesel, and includes a comprehensive assessment of each, as well as a detailed sensitivity analysis of the inputs. The ER range shown in Fig. 37 represents a single high and single low value, where the high value (3.2) includes only the fossil energy inputs to produce biodiesel, and the low value includes all energy inputs. A net energy benefit results when considering only the fossil energy inputs. (ER for biodiesel is most frequently reported for fossil energy inputs only.) The fossil ER of 3.2 is frequently cited and is used as a reference value for comparison in numerous studies. The ER calculated for petroleum production was less than 1, resulting in nearly a four-fold energy benefit for biodiesel compared to petroleum diesel. This study also included a detailed emissions analysis (for CO_2) and comparison between petroleum and biodiesel use in an urban bus. (The LCA results for CO_2 emissions will be discussed in the next section.)

Study No. 6 (Venturi⁽³³¹⁾) compared biodiesel production from rapeseed, soybeans and sunflower seed in Italy, with a range of crop yields, based on differing regional productivity. This study also compared coproduct allocation by energy content with no co-product allocation. The ER falls below one for each feedstock when the no co-product allocation method is used. However, even when co-product allocation is used, sunflower and soybean both result in an energy dis-benefit for low crop yields. Rapeseed is the only favorable energy return for all crop yield ranges when some of the energy use is allocated to the coproducts, due to its assumed higher yields in the growing climate at this location. The results of this study are also compared to ethanol produced from both lignocellulosic and traditional feedstocks. No reference value for petroleum diesel fuel is reported.

Study No. 8 (Bernesson⁽³²⁴⁾) investigated how changing the allocation of co-products affects both energy and global warming impacts of biodiesel. (This study was conducted by a group at the Swedish University of Agricultural Sciences, who also published Study No's. 22 and 30, which were not identified as critical studies due to the narrower scope of each.) This study clearly demonstrates how different allocation methods for co-products dramatically affect the final LCA results. All four allocation methods discussed in Section 8.1.2.2 were applied to small, medium and large-scale production facilities. Results showed that the size of the plant had little impact on the final energy balance of the fuel, but the allocation

method had significant effects. No allocation to by-products resulted in the lower range of the energy return. Any of the allocation methods increase the ER. Not shown in Fig. 37 is the ER for the expanded allocation method, which allows compensation for the energy requirements for the displaced product. When using the expanded allocation method, biodiesel production for all three sizes of plants resulted in a negative energy balance (-2.74, -2.92 and -6.91 for small, medium and large facilities, respectively), indicating that the process is a net supplier of energy. A reference value for ER of conventional diesel is not given in the paper.

Study No. 10 (Janulis⁽³⁰²⁾) investigated transesterification of rapeseed oil in Lithuania. Although the scope is very specific, it is identified as a critical study due to the broad range of impacts quantified, and the frequent citation of this paper throughout the LCA literature. In total, over 20 scenarios were investigated and three different methods of calculating an energy ratio were used. The scenarios included different harvesting yields, use of classic agro-technologies compared to new seed preservation and bio-fertilizer technology, use of methanol compared to ethanol for transesterification, and cold pressing oil extraction versus higher productivity hot pressing technology. The results in Fig. 37 represent all three ER methods that were calculated: the bar at 3.2 is the upper value for ER using the traditional calculation (LHV of fuel/ life-cycle energy inputs). The other two ER calculation methods include different approaches of assessing co-product energy: the second method compares the energy accumulated in all products with total energy consumed; the third method (called the ecobalance) compares the energy in the fuel with the energy related solely to the biofuel production (subtracting energy for co-product production). The second method, which includes all energy contained in co-products, results in high energy ratios, which is why the ER range is well above the average in Fig. 37. This study provides a comprehensive assessment of how changes in technology can help improve the overall energy balance of biodiesel. The results show that REE has slightly higher energy efficiency than RME, and that advancement in technology can help to further improve the energy efficiency compared to biodiesel. By adjusting the allocation of co-products, the energy return may increase by a factor of three.

Study No. 13 (Gartner et al. ⁽³³⁴⁾) investigated 2nd generation biodiesel production via the NExBTL TM process. The evaluation is based on a facility located in Poorvoo, Finland, and utilizes production data collected at the plant, but also includes analysis for average EU conditions. The main difference between locations is the energy mix and use of natural gas. The study investigated both energy and GHG benefits of production from rapeseed oil or palm oil with a variety of origins (grown in Europe or Malaysia). The ER values were reported per ton of NExBTL produced, where the energy content of NExBTL is 44GJ/t. Results for rapeseed showed ER to range from 2.2 to 2.8, depending mainly upon where the rapeseed was grown: a higher ER occurs when rapeseed is grown locally (in the EU) either on land that was set aside, or for natural land that was converted. The lower ER occurs when rapeseed is transported from overseas. The energy savings for producing NExBTL was found to be over 60% relative to conventional diesel.

Study No. 18 (Edwards et al.⁽³⁰⁷⁾) is a complete WTW investigation conducted by the Institute for the Environment and Sustainability in the EU, along with EUCAR and CONCAWE, to aid EU policy decisions regarding alternative fuels. This study includes detailed descriptions of a large array of alternative fuel pathways, with comprehensive appendices for both WTT, TTW and WTW results for each fuel type. The results for biodiesel and the petroleum diesel reference fuel are included in Fig. 37, but the analysis also included synthetic diesel and DME from biomass sources like waste wood and farmed wood. The focus of the study is on policy in the EU, so EU feedstocks of rapeseed and sunflower were investigated. The expanded allocation method was applied in all cases, with glycerin use as both an animal feed and a chemical feedstock being investigated. Additionally, both methanol (to produce RME) and ethanol (to produce REE) were considered as a process fuel, which broadens the range of results for rapeseed compared to sunflower seed.

Study No. 40 (S&T2 Consultants) was also identified as a critical study due to its level of detail.⁽³⁰³⁾ Two separate analyses were performed in the study: one to compare the results of the GHGenius model to the GREET model, depicted by the first range of values in the Fig 37, and one to compare the GHG and ER results for biodiesel production from different feedstocks using the GHGenius model, which is depicted by the two different points for canola and soybean. The model provided detailed assumptions as well as a sensitivity analysis for the results. The sensitivity analysis is not depicted in the figure for ER, but is included in the GHG results discussed in the following section.

Kalnes et al. published two studies for UOP's Ecofining[™] Process: Study No. 24⁽¹⁷⁸⁾ and Study No. 41.⁽³²⁸⁾ Study No. 41 investigated three different feedstocks for the Ecofining[™] process (rapeseed, palm oil, and tallow). It also investigated how using biogas will affect the energy and GHG emissions. Study No. 24 investigated both soy and palm oil. Both compared the renewable diesel results to biodiesel from transesterification of each feedstock, and to low-sulfur petroleum diesel. In each case, the renewable diesel range for each feedstock is reported in Fig. 37 as well as the biodiesel and petroleum diesel reference. The differences in the results from the two studies are quite significant: Study No. 24 reports nearly double the ER for renewable diesel from palm oil than Study No. 41. The most notable difference in the studies is that N₂O emissions were neglected in Study No. 24, but included in Study No. 41. However, this should be more noticeable in GWP than in ER (GWP will be discussed in more detail in the following section). Not enough detail is given in either publication to discern if this is the only difference between the studies. In both studies, renewable diesel results in a favorable energy benefit relative to both its biodiesel counterpart and to conventional diesel. In Study No. 41, using biogas (a coproduct) to produce power that could be used at the processing facility was also investigated, which provides the range of results for palm oil: the lower result does not include the use of biogas, the upper result does. Tallow as a feedstock for the renewable diesel process provides an ER of 9.1. The energy benefit is substantial due to the fact that tallow is considered a waste product from a meat rendering plant, and its only energy inputs come from transportation to the processing facility and from the production of the renewable diesel itself. The three renewable diesel studies (No. 24, 41 and 13) do not show a substantial increase in ER relative to biodiesel production from transesterification, except when using tallow as a feedstock.

Study No. 42⁽³³⁵⁾ (Argonne National Laboratory) reflects the biodiesel pathway results from the GREET model. The only biodiesel feedstock currently included in the GREET model is soy oil. The model calculates both GWP and ER for traditional biodiesel from transesterification and for two different types of renewable diesel: using UOP/Eni Ecofining[™] process and using Canada's SuperCetane[™] process. The results from a total of twelve biodiesel scenarios are included, based on three types of processes and four different allocation methods. The allocation methods investigated include displacement (or expanded allocation), allocation by both energy and market value, and a hybrid case of displacement and allocation in which the sovmeal produced during oil extraction displaces sovbeans for animal feed based on the protein content, and the other co-products produced during the chemical processing to biodiesel are treated by allocation. This hybrid approach provides the upper ER estimate for biodiesel. Of the two renewable diesel cases investigated, the method for SuperCetane[™] generates more co-products (soymeal, fuel gas and heavy oil) per unit of product than does the Ecofining[™] process (which generates soymeal, and naptha/ propane fuel mix). Therefore, the results for SuperCetane[™] are more heavily affected by the co-product allocation method selected. Additionally, the fuel gas generated in the production of SuperCetane[™] is used to power the process, which adds extra energy incentive. The Ecofining[™] process produces fewer co-products, so it benefits the most when an allocation method for the soymeal is used. Although cultivation and fertilization inputs are investigated in the GREET model, no indirect LUC was included in this investigation.

More details on the remaining studies included in Fig. 37 can be found in Appendix VI-1 and VI-2.

8.2.2 Greenhouse Gas Emissions

Frequently in LCA studies of transportation fuels, GHG emissions results are aggregated and reported on the basis of total global warming potential (GWP). GHGs are usually converted to a CO_2 equivalent basis using factors recommended by IPCC ⁽³¹⁹⁾ (shown in Table XIX) or by similar factors. Of the 42 studies included in our literature review, 18 reported GHG impacts or GWP potential. Results from these 18 are shown in Fig. 38. 13 of these studies also have corresponding ER data shown in Fig. 37. The studies that reported a range of results for a particular feedstock are designated by vertical bars; studies reporting a single result are designated by a point. (Note the breaks in the x-axis for Figures 38 and 39.

The 18 LCA studies for GWP shown in Fig. 38 reported GWP as g CO_2 equivalent per MJ of fuel, or other similar value that could be easily converted to this unit. However, some studies investigated the complete WTW lifecycle, while others only completed the WTT portion. A frequent assumption, however, is that the carbon emitted during combustion of biofuels is offset by the carbon uptake during the

Greenhouse Gas	tCO ₂ eq/ t
CO ₂	1
Methane (CH ₄)	23
Nitrous Oxide (N ₂ O)	296
CFC-12	10,600
HFC-134a	1,300
O ₃	6

Table XIX. IPCC GHG Equivalency Factors

plant's growth, resulting in minimal net GWP contribution from combustion (there is some minor contribution to GWP due to other pollutants like NO_x). This is a significant difference when comparing to GWP of conventional diesel fuel, since a large portion of total life-cycle GHG emissions from diesel fuel occurs during combustion.

Although direct comparison among studies is not straight forward, since each study varies significantly in its assumptions and pathways, Fig. 38 still shows a relatively tight range of GWP results, with most of the results falling between 10 and 60 grams of CO_2 equivalent per MJ of fuel produced. The range of conventional diesel GWP values reported in these studies is from 22 to 240 grams of CO_2 equivalent per MJ of fuel; this range is not shown in Figure 38.

The relative GWP difference between the biofuel and conventional fuel reported in each study is illustrated in Fig. 39. (Figs. 38 and 39 consist of slightly different sets of studies due to differences in reporting: many studies only reported a percent increase or decrease, while some reported GWP for biodiesel but not for petroleum diesel). When possible, the complete WTW GHG emissions of biodiesel are compared to the complete life-cycle of the reference diesel fuel. However, the relative impact is widely varied among different studies: several showed a 90% or greater decrease in GHG emissions, while several others showed less than 10% benefit. With the exception of Delucchi's Study No. 34 however, most biodiesel LCA results show a significant improvement in GWP relative to fossil diesel.⁽³²²⁾ The results of Delucchi's model demonstrate the potentially severe impacts of N₂O emissions due to land use change. His model does not include indirect effects, but illustrates the general issues with LUC impacts, which in this case results in a 50% increase in GWP relative to fossil diesel. Indirect impacts have the potential to be even more severe.

Figures 38 and 39 illustrate the extreme variability in LCA results, even when looking at similar feedstocks in similar locations. For example, soybean oil was the feedstock examined in nine of the studies shown in Fig. 38. Three of the five studies which reported a single value correspond quite well with each other, although they are in different locations: No. 1 (Sheehan⁽³¹⁴⁾) and No. 14 (Hill⁽³³⁶⁾) are for production in the U.S.; and No. 37 (Panichelli⁽³³⁷⁾) is for production in Argentina. Study No. 24 (Kalnes⁽¹⁷⁸⁾) for Western European conditions reported a single value GWP about half as large as the above three, while Study No. 34 (Delucchi⁽³²²⁾) reported a GWP about 1.5 times the other three.

The remaining four studies studies (No. 9 is for Italian conditions; ⁽³³⁸⁾ No's. 26, 40, and 42 are for U.S. and Canadian conditions ^(327,303,335)) report a range of values that are generally a bit lower than the single point values. When comparing these values to the reported GWP for petroleum diesel (Figure 39), the variability is even more pronounced. Although the GWP for biodiesel in the NREL study (Study No. 1) was quite high relative to the other soybean LCA models, it also showed a large benefit relative to petroleum diesel in Fig. 39 at about an 80% decrease in GWP. Study No. 42 also results in significant benefits for soy biodiesel at the upper end of its predicted range. Study No. 14 (Hill⁽³³⁶⁾) determined a GWP value comparable to that in the NREL Study, but it resulted in a benefit of only about 43% compared to the reference diesel fuel. Similarly, Study No. 26 (Kreider⁽³²⁷⁾) and Study No. 24 (Kalnes⁽¹⁷⁸⁾) predicted relatively similar GWP values, but No. 26 results in less than 25% reduction in GWP with respect to its reference fuel, while No. 24 predicts nearly a 75% decrease. Study No. 9 (Carraretto⁽³³⁸⁾) also predicted low GWP values, but a broad range of benefits varying from 12 to 75% relative to conventional diesel fuel. Study No. 34 (Delucchi⁽³²²⁾), which predicted the highest GWP by a factor of nearly three, results in a dis-benefit relative to petroleum diesel.



Global Warming Potential

Figure 38. Absolute GWP from 18 Biodistillate LCA Studies

Four studies reported on the absolute GWP for renewable diesel life-cycles: Kalnes et al.^(178,328) on EcofiningTM (Studies No. 24 and 41), Gartner et al.⁽³³⁹⁾ on NExBTL hydrotreating (Study No. 13), and Huo et al.⁽³³⁵⁾ on EcofiningTM and SuperCetaneTM (Study No. 42). Gartner actually reports higher than average GWP for NExBTL compared to other studies, while the EcofiningTM process results in low-range GWP, which is comparable for soy oil from Studies 24 and 42. Kalnes et al. and Huo et al. also report corresponding GWP for biodiesel, and both show that the EcofiningTM process results in a reduction in GWP emissions relative to production of biodiesel from the same feedstocks. The SuperCetaneTM process results in even greater GWP benefit than the EcofiningTM process in Study No. 42. When compared to a

reference diesel fuel, all renewable diesel LCA studies report significant GWP benefits (usually 50% or greater). This is seen in Fig. 39 for Studies Nos. 13, 24, 25, 27, 41, and 42. Reports that include gasification to DME or FTD are also shown in Fig. 39. These technologies show the most consistent results and significant potential for reducing GHGs with respect to conventional diesel (Studies No's. 7, 18 and 30)



GWP Benefit Relative to Reference Fuel

Figure 39. Relative GWP from 24 Biodistillate LCA Studies

8.2.2.1 Critical Studies for GWP

Besides the critical studies previously discussed for energy return that include GWP, additional studies were identified as critical for GWP results based upon similar criteria. The level of detail in the critical studies was enough to provide a breakdown of GWP contributions from each stage of production for comparison. Fig. 40 shows the breakdown by contribution to GWP from agriculture, oil extraction, conversion, transportation and combustion as well as any carbon offsets (due to the carbon neutral principle of CO_2 exhaust emissions or co-product allocations) arranged by feedstock and technology type (transesterification or hydro-processing). The reference diesel fuel value is also shown in Fig. 40 for comparison.

Contributions from each category, as well as total GWP values and amount of reduction relative to fossil diesel vary. Of the three studies included for soybean methyl ester (SME) in Fig. 40, two showed comparable reduction in GWP relative to the fossil reference fuels used, although the total GWP levels varied significantly. Similar reductions relative to reference fuels were demonstrated for the three critical studies for rapeseed methyl ester (RME). Fig. 40 demonstrates how variations in assumptions during each lifecycle stage contribute to differences in the final GWP results for these biofuels. Contributions from the agricultural stage vary most significantly. Delucchi's high N₂O emission rates attribute significant GWP to the agricultural phase, causing a detriment for biodiesel relative to fossil diesel (Study No. 34).⁽³²²⁾

Although the NREL study (Study No. 1) included an analysis of GHG emissions, the total inventory was not converted to equivalent CO_2 emissions, so the reported GWP depicted in Fig. 40 is the straight CO_2 emissions determined, and does not included contributions for N₂O or CH₄. However, the total inventory for these gases is quite small, and would contribute less to total GWP than would the comparable inventory for petroleum diesel. The contributions from the agricultural phase are also quite low in Study No. 1 (see Fig. 40), but most of the N₂O and CH₄ emissions of the life-cycle come from this phase, which would bump up its contribution slightly, if included. Most of the GWP comes from fuel production and final use. The offsets in Fig. 40 are from CO₂ uptake from plant growth, which nearly counteracts all combustion emissions. Thus, the total life-cycle CO_2 emissions in this study are reduced by nearly 80% relative to conventional diesel (see Fig. 39).

The Delucchi report⁽³²²⁾ (Study No. 34) was considered a critical study because of its attention to soil nitrogen emissions. In Delucchi's estimation, the contribution of nitrogen emissions during the agricultural phase is large enough to result in a net-negative GWP effect relative to conventional diesel. Besides the major GHG gases (CH₄, N₂O and CO₂), Delucchi's calculation of total GWP includes other trace gases (CFC-12, HFC-134a, and O₃), which further increase the total GWP dis-benefit of biodiesel compared to conventional diesel. The displaced emissions in Fig. 40 are from both credits to co-products and CO₂ uptake in plant growth.



GWP Breakdown by Category for Critical Studies

Figure 40. Contribution of Individual Life-Cycle Stages to Overall GWP

Study No. 40 (S&T2⁽³⁰³⁾) includes multiple scenarios for canola oil and soy oil. The baseline scenario for both feedstocks showed that biodiesel from canola results in a lower GWP due to its lower nitrogen requirements, leading to lower LUC contributions compared to soy oil. The ranges of GWP in Fig. 38, however, show that canola could have a potentially higher GWP than soy oil. This is due only to higher level of detail in the sensitivity analysis for canola. Therefore, the benefit relative to conventional diesel is

higher for canola than for soy oil because the comparison is made from base case value ranges and not the ranges included in the sensitivity analysis. Only the base-case for soy oil is pictured in Fig. 40 to show the contributions from each life-cycle stage. The contribution from combustion is minimal due to carbon offsets already calculated into the final result. The offset shown in Fig. 40 is due to deductions for co-product allocation. Emissions during the agricultural phase therefore are the most significant contribution to the final reported value for GWP.

The GWP results for Study No. 8 (Bernesson et al.⁽³²⁴⁾) demonstrate how allocation method affects the final product. The range in Fig. 38 includes multiple scenarios for different allocation methods and facility sizes for WTT life-cycle. When allocation methods are used, the GWP between small and large scale facilities only change by about 10%; however, no allocation of by-products result in a 40% difference between the small and large scale facility. The largest amount of CO₂ equivalent emissions results from small-scale facilities with no allocation of co-products, and the smallest amount results when the expanded allocation method is used with large-scale systems. Using the expanded allocation method halves the GHG emissions compared to no allocation. The relative value in Fig. 39 relates the results from the large-scale production facility with physical allocation of co-products after comparison to MK1 diesel oil. The comparison shows a 44% reduction in GHG emissions. Although the comparison is made for slightly different units, it is clear that if no allocation method is used, the results would show little benefit in GHG emissions relative to diesel oil, and may in fact result in a dis-benefit. The main contributions to total GWP are agriculture and combustion (Fig. 40). The offset for co-products is already included in the values provided, so does not appear as a separate bar segment in Fig. 40. This study concludes that largescale facilities provide the best GWP and energy benefits, and that physical allocation methods provide the best-defined inputs. However, this does not take into consideration changes in environmental impacts from displacing other products as the expanded allocation method does. Small changes in assumptions for the expanded method can drastically affect the results.

Study No. 18 (Edwards et al.⁽³⁰⁷⁾) compared biodiesel from sunflower and rapeseed oil. As was found with the ER results, sunflower oil also provides greater GWP benefits compared to rapeseed oil. The range of results for each is based on a variety of assumptions for uses of co-products, and from production using methanol or ethanol for rapeseed. An updated report for this study was published in November, 2008. The updates include additional biodiesel pathways that were not discussed in the original paper. The breakdown for RME when using glycerol as a chemical is shown in Fig. 40 to allow for comparison with a similar breakdown of RME from Study No. 8. This figure shows that the GWP contribution from combustion is nearly completely offset by the assumption of carbon neutrality. However, offsets from co-product allocation are also included in the calculations in the fuel production phase, resulting in a negative GWP contribution by the fuel production phase. Therefore, the main contributions to overall GWP are from agricultural activities. Thus, total GWP shows a 45% benefit relative to conventional diesel.

Studies No. 13 (Gartner ⁽³³⁴⁾), 41 (Kalnes et al. ⁽³²⁸⁾), and 42 (Huo et al. ⁽³³⁵⁾ were identified as critical studies including GWP for biodiesel from hydro-processing. The range of values reported in Fig. 38 for Study No. 13 are for rapeseed as a feedstock from different origins (produced locally on either set-aside land or natural land or imported from overseas) and for different locations for the production facility (the facility at Poorvoo, Finland, or for a location in Europe with average EU conditions). The report does not give a relative diesel value, but states that 1.2-2.5 tons of CO₂ equivalent emissions per ton of NExBTLTM are saved relative to petroleum diesel. These values, with the total CO₂ equivalent emissions from each scenario, were used to estimate a relative diesel value of approximately 84 g CO₂ equivalent emissions per MJ of fuel, which was used to calculate the relative benefits shown in Fig. 39 and Fig. 40. Fig. 40 shows the breakdown for the Poorvoo scenarios with rapeseed growth on set-aside land, although the contributions from each stage are not significantly different for the other scenarios. The offsets to GWP are from both the CO₂ uptake from the growth of the feedstock and from co-product allocation (including

the use of biogas to power the facility). However, no combustion analysis was included in the study. If GHG emissions from combustion were included, it is likely that the total GWP of the fuel would increase, resulting in a lesser benefit compared to the reference fuel than the 70% figure shown here.

Study No. 41 includes scenarios for different feedstocks (rapeseed, palm oil and tallow) for production of both biodiesel and renewable diesel (from the Ecofining[™] process). The range of values for palm oil in Fig. 38 includes only a high and low value that include the use of biogas or not. Figure 38 shows that the production of renewable diesel has a greater GWP benefit than biodiesel for all feedstocks. Tallow has the lowest GWP because it is considered a waste product from the rendering plant; therefore, it has smaller GHG inputs (i.e. it doesn't require agricultural inputs for cultivation), resulting in a 95% decrease in GWP relative to conventional diesel when renewable diesel is produced. Figure 40 shows the breakdown for production of both biodiesel and renewable diesel from rapeseed. The offsets for each are already included in the calculations for total GWP, so are not shown here as a separate bar. There is no GWP contribution for combustion for renewable diesel because the authors assume that all CO₂ emissions are offset from plant growth. There is a small contribution for biodiesel combustion, however, because there is some methanol derived CO_2 , which is of fossil origin. The amount of CO_2 produced during oil production is larger for biodiesel than for renewable diesel, but the amount of GWP resulting from fuel manufacturing is slightly higher for renewable diesel. Renewable diesel, however, has a lower GWP than biodiesel for all feedstocks. Rapeseed results in the highest amount of emissions from agriculture of the three feedstocks because of larger N₂O emissions. Palm oil has the largest GWP of the three feedstocks due to higher amounts of energy required during oil production. This can be reduced, however, if the resulting biogas is used to power the facility.

Study No. 42, as discussed above, includes scenarios for biodiesel, and renewable diesel produced using both the Ecofining[™] process and the SuperCetane[™] process. The range of values in Figure 38 reflects the results from each of the allocation procedures for the three production methods. The displacement and hybrid methods for the SuperCetane process result in an offset to GWP. This range for the SuperCetane[™] process is much greater than for biodiesel or Ecofining[™] due to the large number of co-products that are generated. Both the energy and market value allocation method result in similar GWP values for each of the three different production methods.

Additional details on other studies in the above figures are presented in Appendix VI-1 and VI-2.

8.2.3 Other Common Impact Categories

In addition to GWP and energy requirements, other ecological or resource impacts are often assessed using LCA methodologies. Some of these other categories that are occasionally included in biodiesel LCA studies are discussed briefly below, along with a description of results from the studies in which they were included.

8.2.3.1 Water Resources

Biodiesel production requires water during both growth of the feedstock and during the esterification process. Although water is an important resource, it is not frequently included in biodiesel LCA, likely because of the many uncertainties and regional specificities of water use for biofuel feedstocks. Additionally, it is believed that increased agricultural production of biofuels will not substantially increase the national water-use, although it may have local impacts on already stressed water resources.⁽³⁴⁰⁾ Only two of the literature sources we reviewed explicitly included water use. Sheehan et al. (Study No. 1⁽³¹⁴⁾) found that water use from soybean-derived biodiesel is three times higher than petroleum diesel. However, they also found that wastewater generation is roughly 5 times higher for petroleum diesel than for biodiesel (0.175 L/MJ compared to 0.037 L/MJ, respectively), which has implications for additional environmental impacts. Another U.S. study by Kreider et al. (Study

No. 26 ⁽³²⁷⁾) found that biodiesel production requires about 25 L of water/MJ of fuel, while conventional diesel only requires 0.018 L/MJ.

8.2.3.2 Eutrophication

Eutrophication occurs as a result of excess nutrients (phosphorous and/or nitrogen) applied to increase agricultural yields which runoff into water supplies. In a nutrient-rich environment, plants such as algae grow and decay at a more rapid rate and can cause reductions in water quality or can cause hypoxia or dead zones, such as those that exist in Chesapeake Bay and the Gulf of Mexico.⁽³⁴⁰⁾ The eutrophication potential (EUP) is commonly measured in agricultural LCAs and is sometimes included in biodiesel LCAs. The EUP for biodiesel from vegetable oils increases relative to conventional diesel (Bernesson, ⁽³²⁴⁾ Edwards, ⁽³⁰⁷⁾ and Hansson ⁽³³⁰⁾). Ahlgren et al. ⁽³⁴¹⁾ found that biodiesel produced from organic crop growth reduces EUP compared to conventional diesel. Additionally, using waste products such as waste vegetable oil shows an EUP benefit relative to conventional diesel (Niederl⁽³²⁵⁾).

8.2.3.3 Acidification

The acidification potential (ACP) also is increased slightly for biofuels. Acidification results when nitrogen, sulfur oxides, and ammonia that are released as a result of fertilization during plant growth are oxidized in the atmosphere to form acids. This can lead to "acid rain" which lowers the pH of soils and water. Since these types of emissions are only associated with agricultural activities, biodiesel fuels generally show an increase in ACP compared to petroleum diesel. ^(339,324,307,330) Again, use of waste vegetable oils and organic cropping methods can reduce these effects. ^(325,341)

8.2.3.4 Photochemical Ozone Creation Potential

A handful of studies included additional environmental impact categories. Although Photochemical Ozone Creation Potential (POCP) is an important environmental impact, it is rarely assessed. POCP, which relates to smog formation, increases due to ozone formation from NOx and hydrocarbon emissions from incomplete combustion. In three studies, it has been reported that biodiesel shows a small POCP benefit relative to diesel fuel.^(339,324,325) However, considering the variability of results in the biodiesel emissions literature (see Section 7 above), a definitive conclusion about POCP benefits cannot be reached.

8.2.3.4 Other Impact Categories

Additional LCA impact categories include abiotic depletion, ozone layer depletion, human toxicity, waste, fresh water aquatoxicity, and habitat disruption. These categories are rarely reported in the literature. A small benefit for abiotic depletion for biodiesel was reported by Niederl⁽³²⁵⁾. An increase in ozone layer depletion for biodiesel relative to conventional diesel was reported by Gartner.⁽³³⁹⁾ Harding et al.⁽³⁴²⁾ reported values for abiotic depletion, ozone layer depletion, human toxicity and aquatoxicity, but did not relate them to a reference fuel. A recent report for the California Environmental Protection Agency summarized numerous environmental issues associated with the transport and fate of biodiesel, though most of those issues were not addressed on a life-cycle basis.⁽³⁴³⁾

9. Recap of Renewable Diesel Issues

While discussion of renewable diesel has been included throughout this report, many topics have dealt primarily with biodiesel. In this section, we focus more directly on renewable diesel fuels, emphasizing areas where they differ from biodiesel.

The definition of biodiesel is clearly understood (by ASTM, EPA, and other groups) to be "mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats." In contrast, there is no single, universally accepted definition of renewable diesel.⁽⁹⁾ However, one common definition of renewable diesel is "Non-fossil mid-distillate hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats." (Mid-distillates produced from lignocellulosic feedstocks via pyrolysis and gasification processes may also be defined as renewable diesel, but these materials are outside the scope of this study.) Other terms used synonymously with renewable diesel include "green diesel" and hydrotreated vegetable oil (HVO).

Two general approaches are used for hydroprocessing of triglycerides to produce renewable diesel: (1) "bio-only" processing and (2) co-processing with petroleum-derived materials. Both approaches have been studied quite extensively, and are in commercial use today. Examples of the "bio-only" approach include Neste Oil's NExBTL^(175,176) and UOP's Ecofining[™] technology.^(177,178) Examples of the co-processing approach include the ConocoPhillips (COP) process⁽¹⁸¹⁾ and the Petrobras H-Bio process.⁽⁹⁾

While exact processing conditions are proprietary, all renewable diesel production technologies involve catalytic hydrotreatment under elevated temperatures and pressures. Operating severity is sufficient to saturate all olefinic groups; remove all sulfur, nitrogen, and oxygen groups; and produce paraffinic hydrocarbons as the major product. Oxygen is removed in the form of CO, CO₂, and H₂O – with the relative amounts of these species depending upon catalyst type and operating severity. Light hydrocarbon gases (methane, ethane, and propane) and naptha are produced in some cases. An interesting feature of renewable diesel is the presence of odd-numbered carbon molecules – especially C_{15} and C_{17} . These arise from de-carboxylation of the even numbered fatty acid groups contained in the triglyceride feedstocks.

In comparison with biodiesel production, a significant advantage of renewable diesel production is avoidance of glycerol formation. Under hydroprocessing conditions, the glycerol-forming units within the triglyceride feedstocks are converted to CO, CO₂, and light hydrocarbons. Another processing advantage is that no alcohol is used in producing renewable diesel, as is required in production of biodiesel. In addition, hydroprocessing to produce renewable diesel is generally more tolerant of low quality feedstocks -- such as those containing high free fatty acid (FFA) levels -- compared to biodiesel production. On the other hand, feedstocks with high FFA contents introduce concerns about metallurgical stability in hydroprocessing units. Other disadvantages of renewable diesel production include high capital costs of the process equipment, and the need to produce and deliver hydrogen.

Other distinctions between biodiesel and renewable diesel involve the location, infrastructure, and scale of operation. Renewable diesel is generally produced within (or adjacent to) a petroleum refinery, which provides logistical flexibility in terms of blending, storing, and transporting fuels. In addition, refineries possess well-equipped laboratories (along with trained personnel) that are required for product quality testing. Typical refineries are much larger than biodiesel plants, thus their feedstock demands for producing renewable diesel (even at a low blend level) are greater than for biodiesel production. This fact effectively limits the location of renewable diesel production to places having access to large supplies of vegetable oils and animal fats – such as near shipping ports.

Biodiesel typically contains about 11% oxygen, in the form of methyl esters, whereas renewable diesel has no oxygen. As a consequence, the energy content per unit mass of renewable diesel is considerably higher than biodiesel, and is similar to that of conventional, petroleum diesel. However, renewable diesel has substantially lower density than biodiesel (specific gravity of 0.78 compared to 0.88), so that on a unit volume basis, the energy contents of renewable diesel and biodiesel are similar, with both being substantially lower than petroleum diesel.

Consisting largely of straight chain paraffinic molecules, renewable diesel has very high cetane numbers – typically in the range of 70-90. [One technology, developed by Canada's CANMET Energy Technology Centre (CERT) produces a product called SuperCetane[™] which has a reported cetane of 100.⁽³⁴⁴⁾] Because of this, one useful application of renewable diesel is upgrading sub-cetane blendstocks.

A negative consequence of renewable diesel's straight chain paraffinic nature is poor low temperature operability, as defined by pour point and cloud point test procedures. In this respect, renewable diesel and biodiesel are similar, with both generally having poorer low temperature operability compared to petroleum diesel. However, this problem may be somewhat more easily mitigated with renewable diesel, by modification of the hydroprocessing conditions to introduce a greater degree of branching within the paraffinic structures.

The complete saturation of olefinic groups by hydroprocessing results in excellent oxidative stability for renewable diesel. At the same time, severe hydrotreatment removes all heteroatoms (S, N, and O) which provide improved lubricity compared to hydrocarbons. Consequently, renewable diesel has poorer lubricity performance than biodiesel. In this regard, renewable diesel is similar to ULSD (and to Fischer-Tropsch GTL products). Renewable diesel requires additive treatment, or mixing with higher lubricity blendstocks, to achieve satisfactory lubricity performance.

ASTM has established sets of standard specifications for B100 (ASTM D 6751) and for B6-B20 blends (ASTM D 7467). No separate specifications have been established for renewable diesel. However, middistillate fuels containing renewable diesel must meet the standard specifications for diesel fuel (ASTM D 975). Since renewable diesel is composed of hydrocarbons virtually identical to those in petroleum diesel, blending of renewable diesel is possible at any level. Actual, in-use blending levels of renewable diesel have not been surveyed, but are believed to be quite low, such as R5 and below.

With renewable diesel being a relatively new fuel, there is little information available regarding its stability, low-temperature operability, materials compatibility, or other performance attributes. Based upon a few published reports of emissions performance, it appears that renewable diesel and biodiesel offer similar benefits of reduced HC, CO, and PM compared to petroleum diesel – generally 10-20% reductions using 20% blends. The impacts on NOx emissions are smaller and hard to discern. Considering the large variability of results across different engine types, operating modes, and test programs, the NOx effects of both renewable diesel and biodiesel at a 20% blend level are close to zero.

Life-cycle analysis (LCA) for energy return (ER) and global warming potential (GWP) show significant benefits for both biodiesel and renewable diesel, compared to petroleum diesel. Based upon the few studies reported to date, (and the large variability among these studies), no clear distinctions can be made between biodiesel and renewable diesel. LCA is a rapidly growing field of study, and much more information is likely to become available in the future.

10. Summary and Conclusions

Presently, there is considerable interest in the broad topic of biodistillates. Numerous facets of this topic constitute active and growing areas of investigation within the research, policy, and regulatory communities. Our review of the biodistillate literature (primarily technical literature) revealed rapidly increasing numbers of papers and reports over the past few years. Given below are brief summaries and major conclusions from individual sections of our review.

10.1 Policy Drivers

For reasons of energy security, sustainability, diversity, and climate change mitigation, many countries and regions have developed policies to promote greater production and use of biodistillate fuels. In the U.S., the dominant policy driver is the Energy Independence and Security Act of 2007, which requires 0.5 bg/y of biodiesel by 2009, and 1.0 bg/y by 2012. This larger amount represents about 2.5% of total U.S. on-road diesel fuel usage. European Union Directives currently require 2.0% biofuels content in all transportation fuels, ramping up to 5.75% by 2010.

Numerous other countries have also implemented policies encouraging (or requiring) increased biodistillate usage. Some of the most aggressive actions have been taken by China, India, and Brazil. However, unlike the U.S. situation, it appears that the biodistillate goals of many countries are overly optimistic, and will not be achieved within the projected time timeframe. Existing policy-based goals forecast total biodistillate usage (in the U.S., Europe, China, India, and Brazil) of about 23 bg/y in 2020. Based upon our assessment of the situation, we forecast a much lower usage of about 7 bg/y in 2020.

10.2 Biodiesel Volumes and Feedstocks

Growth in biodiesel production has been dramatic in recent years, especially in Europe and the U.S. Global production has increased from approximately 0.5 bg/y in 2005 to 2.5 bg/y in 2007. While numerous triglyceride feedstocks have been investigated for biodiesel production, only a few are in widespread commercial use. The dominant feedstock in the U.S. is soybean oil, with far lesser amounts of other seed oils, used cooking oils, and animal fats being used. In Europe, the dominant feedstock is rapeseed oil.

Biodiesel production capacity has grown much faster than actual production volumes. Excess capacity has become a serious problem within the biodiesel industry. Current production in the U.S. and Europe is well below 50% of capacity. This is driven mainly by limited availability and high costs of current feedstocks. Consequently, there is tremendous interest in developing alternative feedstocks, particularly those that do not have concurrent uses as food. Two of these so-called, 2nd generation feedstocks that are receiving great attention are jatropha and microalgae. It is likely that commercially produced biodistillates from these feedstocks will begin to appear in the marketplace within the next 5 years.

With its principal feedstocks being agriculturally-produced materials, the biodiesel industry has traditionally been viewed as an extension of agriculture. Until very recently, most biodiesel manufacturing plants have been small (< 5 mg/y) and located in crop-producing regions. The industry is now undergoing a significant change, with introduction of much larger manufacturing plants (> 20 mg/y) located near ports with access to world-wide feedstocks. Major energy and fuel companies, such as BP, Chevron, ConocoPhillips, Marathon, and Shell are now beginning to participate in biodiesel activities. Additionally, production and use of renewable diesel (produced via hydroprocessing of triglyceride feedstocks) are becoming more common.

In most locations, the predominant use of biodiesel is as a low-concentration blend with petroleum diesel. Concentrations of 2% (B2), 5% (B5) and 20% (B20) are most common. Only in Germany and Austria is neat biodiesel (B100) commonly employed as a transportation fuel.

10.3 Biodistillate Production Technologies

Due to their high viscosity levels (and other related problems), raw vegetable oils are generally not suitable for use as a fuel in a diesel engine. Much lower viscosities result from transesterifying these oils with alcohols to produce esters. Mainly for reasons of cost, methanol is the preferred alcohol. The resulting fatty acid methyl esters (FAME) are the principal constituents of biodiesel. Typical biodiesel

production conditions involve a large excess of methanol, use of hydroxide or alkoxide homogeneous catalyst, mild heating (50-60 °C), gravity separation, water washing, and distillation. However, numerous operational variations of these parameters are possible (and are employed). Certain feedstocks, such as used cooking oils and animal fats, are more difficult to handle, and may require additional processing steps.

The literature contains numerous reports of studies investigating improvements in the production of biodiesel. Most commonly discussed are uses of alcohols other than methanol, co-solvents, heterogeneous catalysts, supercritical methanol conditions, and ultrasonic or microwave heating. While many of these improvements have been demonstrated on a laboratory scale, none of them is in common commercial usage.

The transesterification route for biodiesel production unavoidably leads to co-production of glycerol. The presence of glycerol in biodiesel can lead to performance problems. Hence, it is critical to remove glycerol to achieve acceptable, on-spec product. This adds processing complexity and cost, and results in a co-product stream having relatively little value.

Hydroprocessing of triglycerides is an alternative route to biodistillates that does not involve alcohols or glycerol production. Unlike biodiesel, which consists of methyl esters, hydroprocessed triglycerides produce hydrocarbons that are virtually identical to those found in petroleum diesel. This hydroprocessed fuel is generally known as renewable diesel, as opposed to biodiesel. Production of renewable diesel is most conveniently accomplished within an integrated petroleum refinery.

While still in the R&D stage, there is also interest in other thermal processing routes to biodistillates, primarily through pyrolysis and gasification. Triglycerides can be pyrolyzed (or thermally cracked) to produce biodistillates, but of greater long-term interest is treatment of lignocellulosic materials. Although considerable work is being done in these areas, no commercial applications are in use today.

10.4 Fuel Properties and Specifications

The properties of biodiesel fuel are largely dictated by the chemical composition of the fatty acid methyl esters comprising the fuel. Because various triglyceride feedstocks differ substantially in their composition, the properties of the resulting biodiesel fuels also vary. Two of the most important chemical parameters affecting the overall fuel properties are carbon chain length and degree of unsaturation (carbon-carbon double bonds) within the FAME molecules.

Biodiesel typically contains about 11% oxygen, in the form of methyl esters. As a consequence, it has lower mass energy content than petroleum diesel – by about 10%. However, due to its somewhat higher specific gravity, biodiesel's volumetric energy content is only about 5-6% lower than that of petroleum diesel. Renewable diesel, containing no oxygen, has a mass energy content very similar to petroleum diesel. However, the volumetric energy content of renewable diesel is considerably lower than that of petroleum diesel (due to its lower specific gravity) and is similar to the volumetric energy content of biodiesel.

Standard specifications for biodiesel fuel have been developed, and are continuing to evolve, in many countries. In the U.S., current biodiesel (B100) specifications are defined by ASTM D 6751-08; European specifications are defined by EN 14214. At present, the U.S. is the only country having separate specifications for biodiesel blends: ASTM D 7467 applies to B6-B20 blends. In most countries (including the U.S.), biodiesel blends of 5% and lower must comply with the specifications established for conventional diesel fuel.

Biodiesel fuel standards include numerous different specifications and test methods, many of which are meant to ensure that the transesterification reaction and product clean-up steps were performed satisfactorily. For example, specifications for water content, viscosity, flash point, methanol content, sulfated ash, acid number, glycerine content, and others are meant to ensure high purity FAME product. The European standards include explicit specifications for various metrics of FAME unsaturation, such as iodine number and concentration of linolenic acid methyl ester. ASTM standards do not include these tests, but do incorporate an oxidative stability test (the Rancimat Test) that may be regarded as a surrogate test for unsaturation. Ensuring full compliance with biodiesel standard specifications requires extensive laboratory testing, which is not practical for many small producers. Nevertheless, it is important for every producer to conduct a subset of most critical product quality tests on each fuel batch, with more extensive outside testing done periodically.

Adhering to established quality control/quality assurance (QC/QA) measures is critical to ensuring satisfactory biodiesel quality in the marketplace. In the U.S., the BQ-9000 Quality Management System was recently developed to define acceptable QC/QA measures. BQ-9000 includes separate sets of requirements for B100 producers and B100 marketers. While still quite new, it appears that voluntary participation in the BQ-9000 Quality Management System is growing.

10.5 In-Use Handling and Performance of Biodiesel Fuels

All transportation fuels require proper handling and adherence to "good housekeeping practices" to ensure satisfactory quality in the field. However, with biodiesel, some extra precautions are warranted, due to this fuel's higher solvency, propensity to pick up water and disperse sediments, and inherent oxidative instability. Some reported field problems can be traced to poor handling and housekeeping practices.

Most in-use biodiesel is produced by blending B100 and petroleum diesel. Various methods of blending are commonly employed, but in-line blending at a fuel terminal is the preferred approach, as this provides the best control and most accurate blend compositions. Recent surveys of in-use biodiesel have shown significant inaccuracies of blending, with some reported B20 blends actually containing much more or much less than 20% biodiesel.

U.S. fuel quality surveys have also revealed problems with off-spec biodiesel in the marketplace, with poor oxidative stability being one of the main concerns. The most recent surveys (conducted after the Rancimat Test method was included in ASTM D 6751) showed improved quality overall, with fuel manufactured by large producers (>1 bg/y) nearly always meeting all specifications. Fuel produced by small "Mom and Pop" operators continues to be a concern, as many of these producers do not have the tools or expertise to perform laboratory quality control tests.

Instability of biodiesel is a complex problem, with several contributing factors. No single laboratory test is able to assess all important degradation pathways, hence numerous tests have been developed and are used for different purposes. The degree and type of unsaturation within the FAME molecules are important determinants of instability. Antioxidant additives are useful for improving the stability of biodiesel, with synthetic materials generally being more effective than antioxidants naturally occurring in vegetable oils.

For many biodiesel users, low temperature operability is the greatest in-use concern, as this can lead to filter plugging and engine shutdown. Numerous laboratory tests have been developed to assess low temperature operability; the most common ones being cloud point (CP), pour point (PP), and low temperature filterability test (LTFT). In general, biodiesel has somewhat poorer low temperature operability than petroleum diesel, though the extent of the difference varies substantially based upon the

unique chemical composition of the biodiesel in question. Visible wax formation, which defines CP, is caused by crystallization of the least soluble species – namely, saturated, long-chain FAME. Unsaturated FAME molecules are much less prone to crystallize. Hence, to some degree, there exists a tradeoff between fuel stability (enhanced by saturated FAME) and low temperature operability (diminished by saturated FAME). Low temperature operability of biodiesel can be improved by greater dilution with petroleum diesel, use of cold flow improver additives, and use of ethanol rather than methanol in the transesterification process.

While greatly reduced compared to raw vegetable oil, the viscosity of biodiesel is usually still higher than that of petroleum diesel. This can have adverse impacts with respect to fuel injection and atomization, particularly under low temperature conditions.

In general, biodiesel fuel provides excellent lubricity in fuel injection systems. This is due both to inherent properties of FAME itself, and to high lubricity trace constituents (such as free fatty acids) that are present as contaminants in the fuel. Use of low concentration biodiesel blends, such as B2, is an effective way to achieve satisfactory lubricity in today's ultra-low sulfur diesel (ULSD). By itself, ULSD can have quite poor lubricity, because the severe hydroprocessing used to achieve very low sulfur levels also removes naturally-occurring trace species having high lubricity. In the same way, renewable diesel, which is produced by hydroprocessing similar to that used for ULSD, also has poor lubricity. However, the lubricity of both ULSD and renewable diesel can be improved by means of fuel additives, or by mixing with other blendstocks having higher lubricity.

There have also been concerns about materials compatibility with biodiesel, as well as engine wear, corrosion, microbial growth, and other adverse impacts. While there is documented evidence supporting some of these claims, it is likely that in most cases, off-spec fuel and poor overall fuel housekeeping were also involved. (It is important to remember that the ASTM D 6751 standard specification for biodiesel did not include an oxidation stability test until 2007.)

While exceptions are possible, it appears that acceptable in-use handling and performance of biodiesel is best achieved by strict adherence to established fuel specifications and implementation of good fuel housekeeping practices. Additionally, to minimize concerns regarding fuel stability, viscosity, materials compatibility, and others, it is prudent to limit the biodiesel composition to B20 and below.

10.6 Exhaust Emissions Impacts

Reduction of exhaust emissions has been one of the drivers for biodiesel fuels for many years. Compared to conventional petroleum-derived diesel fuel, most literature reports indicate 10-20% reductions in CO, HC, and PM emissions when using B20 blends, with larger benefits at higher blend levels. Similar benefits are observed with both LD and HD engines/vehicles, though individual results vary widely from one study to the next. Although data are much more limited for renewable diesel cases, it appears that similar benefits in reduction of CO, HC, and PM are observed with these hydroprocessed fuels.

The fuel effects upon NOx emissions are much smaller, and difficult to discern. Our assessment of HD NOx results suggests that biodistillates have no effect at low levels (B20) but increase NOx slightly (2-3%) at B100 levels. LD results suggest a more consistent NOx increase of 10-15% for B20 and B100, respectively, though the high variability in these emissions results makes these conclusions somewhat questionable. Also, due to the high variability, it is not possible to discern clear trends in fuel effects with changes in engine technology or model year. Based upon the small amount of available information, it appears that the emissions effects of renewable diesel are not greatly different from the effects of biodiesel. More work is needed in this area to assess whether significant differences exist.

Much less information is available regarding non-criteria pollutant emissions from use of biodistillate fuels. Most mobile source air toxics (MSAT) data relate to formaldehyde and acetaldehyde. As with the criteria pollutants, these aldehyde results are highly variable, showing both increases and decreases compared to use of conventional diesel. However, the majority of the results indicate a slight decrease in aldehyde emissions when using B20, and a larger decrease when using B100. A more substantial body of emissions data is necessary to confirm (or refute) these observations.

10.7 Life-Cycle and Land Use Impacts

Life-cycle assessments (LCA) of "well-to-wheels" energy inputs and GHG emissions are now recognized as important tools for understanding the relative benefits of biodistillate fuels compared to conventional fuels. However, LCA models are very data intensive, and require numerous inputs having high uncertainty. Some of the most critical inputs are in areas that are most uncertain – such as assumed agricultural practices and their emissions, impacts attributed to co-products, and land use changes (LUC). Many LCA models include treatment of direct LUC, such as emissions resulting from conversion from one crop to another in the U.S. However, treatment of indirect LUC, such as conversion of pastureland in Brazil to soybean fields in response to U.S. fuel demand, is in its infancy. Although there are U.S. regulatory requirements to consider indirect effects in assessing the life-cycle impacts of biofuels, no standard methodology has been established to do so. Progress is being made in this direction by attempting to merge global economic models with LCA models.

Well-to-wheels LCA studies of energy inputs and GHG emissions are often separated into two parts: (1) well-to-tank and (2) tank-to-wheels. These two steps are sometimes referred to as upstream and downstream, or production and use. For conventional fuels, a considerable portion of the total life-cycle GHG emissions occurs during the tank-to-wheels stage, as the fuel is combusted to produce CO_2 . For biofuels, this component is generally ignored (or offset), based on the assumption of carbon neutrality, meaning that the CO_2 in combustion emissions is equivalent to the CO_2 recently extracted from the atmosphere to grow the biomass. Consequently, for biofuels, well-to-tank and well-to-wheels GHG emissions are very similar.

Allocating some fraction of life-cycle energy inputs and GHG emissions to co-products is reasonable and necessary, but also constitutes a major area of disagreement among different LCA models and modelers. Of the various allocation approaches used, the "expanded allocation method" seems most realistic, in that it attempts to credit energy and emissions from the processes used to produce products now being replaced by biofuel co-products. However, this approach requires additional assumptions, and further convolutes the LCA methodology.

To some degree, LCA modeling suffers from the perception (and perhaps reality) that by proper tailoring of input assumptions and methodologies, the practitioner can derive any outcome that is desired. Because of this, direct comparison of life-cycle energy inputs and GHG emissions across different studies is often problematic. More instructive is comparison of the relative differences between biodistillates and conventional diesel fuel reported by different investigators.

Life-cycle energy results are typically reported as energy return on investment (EROI, or more simply, ER), meaning the heating value of the final biofuel divided by the total energy inputs involved in producing, distributing, and using the fuel. Typically, ER values for conventional diesel fuel are slightly under 1.0. Our analysis of 19 LCA studies gave an overall average ER value of about 3.1 for biodistillates, indicating substantial benefits for these fuels (both biodiesel and renewable diesel) in terms of life-cycle energy. However, the range of ER benefits is extremely large, depending upon assumptions and methodologies chosen. There are even a few cases where biodiesel scenarios gave lower ER values than the reference conventional fuel.

LCA results for GHG emissions are usually expressed in terms of relative global warming potential (GWP). This metric includes not only the effects of CO_2 , but also of other GHG emissions that occur over the entire life-cycle. Emissions of N₂O (mostly from soil) are especially important, although there are significant uncertainties about the actual emissions levels of this potent greenhouse gas. In nearly every case where comparisons are possible, the life-cycle GWP of biodistillate fuels is lower than for conventional fuel. This is true for both biodiesel and renewable diesel fuels. However, as with ER, the reported GWP benefits of biodistillates vary widely from one study to the next. In most of the 18 studies we investigated, the GWP benefits of the biodistillate fuels ranged from 10% to 90% reduction compared to conventional diesel, with an overall average value of about 60%. There are a few exceptions, mainly due to assumptions of high N₂O emissions, where biodiesel scenarios showed overall GWP dis-benefits compared to conventional diesel.

Besides energy inputs and GWP, LCA analyses can be used to evaluate additional environmental impacts related to water resources, eutrophication, acidification, and other outcomes. While still a fairly immature area, these types of analyses are increasingly being investigated to give a more complete picture of biofuels' total life-cycle impacts.

11. Information Gaps and Recommendations

Many non-edible triglyceride feedstocks are being investigated for 2nd Generation biodistillate
production. The two currently receiving the greatest interest are microalgae and jatropha, though
many others are also being explored, including castor oil, karanja, pongamia, soapnut oil, and others.
Large scale production of these feedstocks raises issues about sustainability and environmental
impacts. Additionally, the composition and properties of biodistillates (particularly biodiesel)
produced from these new triglyceride feedstocks require investigation. As a point of illustration,
castor oil is unique in containing significant amounts of ricinoleic acid, which is likely to impact the
composition of biodistillates produced from it.

<u>Recommendation:</u> CRC and its member companies should monitor developments in these areas, but no specific actions are recommended at this time.

2. Lignocellulosic materials are increasingly being investigated as feedstocks for production of transportation fuels, including biodistillates. While most activity has been directed towards production of alcohols or Fischer-Tropsch derived hydrocarbon products, there is growing interest in thermal processes to produce pyrolysis oils that could be feedstocks for distillate fuels. Such pyrolysis-derived fuels raise concerns about product stability, handling, and blending. Additionally, the performance and emissions impacts of such fuels are largely unexplored.

<u>Recommendation:</u> CRC and its member companies should monitor developments in these areas. Once pyrolysis oils are being used as feedstocks for fuel production, the properties and impacts of the derived biodistillates should be investigated.

3. Field surveys of biodistillate fuels have revealed problems with the quality of some fuels in the marketplace. The occurrence of "off-spec" fuels may be more common than is acceptable, particularly fuels produced and marketed by small operators. ASTM biodiesel standards have been developed or modified recently to address known problems in this area. For example, the Rancimat oxidative stability test was added to the standard specifications for B100 in 2007. In 2008, a new set of standard specifications was introduced (ASTM D 7467) for B6-B20 blends. No large-scale, systematic field survey of biodiesel fuel quality has been conducted since these new standards were introduced.

<u>Recommendation:</u> CRC and its member companies should consider participating in a coordinated field survey project to evaluate the quality of biodiesel and biodiesel blends in the marketplace.

4. Accurate blending of biodistillates with conventional diesel is sometimes problematic, as indicated by analyses of fuels drawn from the marketplace. To promote public confidence and monitor compliance with renewable fuel standards, it is important to have a rapid, accurate, and inexpensive means of determining the biodiesel and renewable diesel contents in finished fuel blends.

<u>Recommendation:</u> CRC and its member companies should consider developing a real-time sensor to monitor both biodiesel and renewable diesel contents in finished biodistillate blends.

5. Renewable diesel is now being produced commercially, and is being blended into finished transportation fuels. Several different hydroprocessing approaches are being used to produce these blendstocks. It is expected that the chemical compositions and physical properties of renewable diesel will vary with process conditions. These differences may also affect the handling and performance of renewable diesel fuels.

<u>Recommendation</u>: CRC and its member companies should consider funding a study to investigate the relationships between hydroprocessing conditions and the handling/performance properties of the renewable diesel. Detailed chemical compositions should be determined and related to attributes such as low temperature operability, lubricity, stability, materials compatibility, wear, and other metrics.

6. Exhaust emissions impacts of biodistillate fuels continues to be a subject of great interest. Based upon previous testing and reviews, a consensus has arisen that use of biodiesel significantly reduces HC, CO, and PM emissions, but slightly increases NOx. Upon inclusion of more recent data, as was done in this review, the emissions reduction benefits for HC, CO, and PM are still apparent, though perhaps reduced. For NOx, however, we now see no effect in HD engines at low blend levels (B20 and below), and only a slight increase (2-3%) with B100. Based upon the limited information currently available, the emissions impacts of biodiesel and renewable diesel appear to be similar. However, two important caveats should be stressed: (1) emissions results are highly variable with engine type, operating condition, fuel source, emissions control systems, and other parameters, and (2) very little emissions work has been conducted using modern, low-emitting engines and biodistillate fuels that comply with today's ASTM standards.

<u>Recommendation:</u> CRC and its member companies should monitor current emissions research (sponsored by CARB and others) investigating the effects of typical biodistillate fuels in modern HD engines. An additional test program may be considered (perhaps as an add-on to the ACES Program) in which biodistillate emissions effects are investigated in a 2010-certified HD engine. Differences in emissions between biodiesel and renewable diesel should be systematically investigated.

7. Compared to the criteria emissions (CO, HC, NOx, and PM) very little is known about the impacts of biodistillates upon mobile source air toxics (MSAT) emissions. Consisting of oxygenated species, it might be expected that carbonyl emissions would increase from use of biodiesel. However, the literature is inconsistent on this point – some studies report increased carbonyls, while others do not.
<u>Recommendation</u>: CRC and its member companies should consider sponsoring a carefully-controlled laboratory test program to investigate the effects of biodiesel and renewable diesel upon MSAT emissions from one or more modern diesel engines. Emissions of carbonyls are of greatest concern, but impacts on other species – including aromatics, olefins, and PM – may also be of interest.

8. Questions have been raised in the past about the impacts of biodistillates upon engine performance and wear. Some studies (including those sponsored by CRC) have demonstrated problems, although most adverse effects are likely related to poor fuel housekeeping or use of off-spec fuels. No major studies in this area have been conducted using fuels meeting today's ASTM standard specifications.

<u>Recommendation:</u> CRC and its member companies should consider sponsoring a carefully designed test program involving modern engines and fuel system materials to investigate possible adverse effects of biodistillates that (1) meet and (2) do not meet all applicable ASTM standard specifications. Field performance under realistic, low temperature conditions should also be considered.

9. LCA studies are becoming increasingly common for assessing the total energy inputs and environmental impacts of a particular fuel. Different LCA approaches, using a wide range of input assumptions, can lead to dramatically different results. In particular, assumptions about land use changes and co-product allocation are extremely influential in determining the final LCA results.

<u>Recommendation:</u> CRC and its member companies should monitor developments in this area, and be prepared to critique LCA studies performed by other groups. To ensure reasonable assumptions and proper treatment of all fuels, CRC may wish to sponsor research in this area.

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13. List of Acronyms and Abbreviations

ACP	Acidification potential
API	American Petroleum Institute
ASTM	American Soc. for Testing and Materials International
B100	Neat (100%) biodiesel
B20	Blend of 20% biodiesel in petroleum diesel
BG/Y	Billion gallons per vear
BHP	Brake horsepower
BOCLE	Ball on cylinder lubricity evaluator
BTL	Biomass-to-liquids
BTU	British thermal unit
CARB	California Air Resources Board
CCI	Calculated cetane index
CEN	European Committee for Standardization
CFI	Cold flow improver
CFPP	Cold filter plugging point
CI	Compression ignition
CIDI	Compression ignition
CN	Cetane number
CO	Carbon monoxide
CO	Carbon dioxide
CP	Cloud point
CRC	Coordinating Research Council
DARPA	Defense Advanced Research Projects Agency
DI	Direct injection
DOF	U.S. Department of Energy
FRAMM	ERG Biofuel Analysis Meta-Model
EGR	Explaint as recirculation
EUK	Exhaust gas recirculation Engine Manufacturers' Association
EN	European Norm
	LUS Environmental Protection Agency
EPOI	Energy return on investment (also called ED)
EKUI	Energy return on investment (also caned EK)
	European Union
EUP	Europhication potential
FAEE	Fatty acid ethyl ester
FAME	Faily acta methyl ester
FCC	Fluid catalytic cracking
FFA	Free fatty actor
FID	Fischer Tropsch diesei
GHG	Greenhouse gas
GREEI	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GIL	Clabel Wenning Defection
GWP	Global warming Potential
HDDV	Heavy-duty diesel venicle
HEV	Hybrid electric vehicle
HFKK	High frequency reciprocating rig
HVU	Hydrotreated vegetable oil
ICE	Internal combustion engine
IDI	Indirect injection

IPCC	Intergovernmental Panel on Climate Change
LAD	Low aromatic diesel fuel
LCA	Life-cycle assessment
LCO	Light cycle oil
LDDV	Light-duty diesel vehicle
LTFT	Low temperature flow test
LUC	Land Use Change
MB/D	Million barrels per day
MG/Y	Million gallons per year
MMT/Y	Million metric tons per year
MSAT	Mobile source air toxic
MW	Molecular weight
N_2O	Nitrous oxide
NAAQS	National ambient air quality standard
NBB	National Biodiesel Board
NCWM	National Conference on Weights and Measures
NERD	Non-ester renewable diesel
NO	Nitric oxide
NO_2	Nitrogen dioxide
NOx	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_3	Ozone
OSI	Oxidative Stability Index
РАН	Polycyclic aromatic hydrocarbon
PM	Particulate matter
PM_{10}	PM with diameter $\leq 10 \mu m$
PM ₂₅	PM with diameter ≤ 2.5 µm
POCP	Photochemical ozone creation potential
РР	Pour point
RME	Rapeseed methyl ester
ROW	Rest of world
SAE	Society of Automotive Engineers International
SCR	Selective catalytic reduction
SCTE	Single cylinder test engine
SG	Sterol glucoside
SME	Sov methyl ester
SI	Spark ignition
SOx	Oxides of sulfur
SVO	Straight vegetable oil
TAN	Total acid number
TDP	Thermal de-polymerization
TTW	Tank-to-wheels
ULSD	Ultra-low sulfur diesel fuel
VGO	Vacuum gas oil
VOC	Volatile organic compound
WAP	Wax appearance point
WTE	Waste-to-energy
WTT	Well-to-tank
WTW	Well-to-wheels
WVO	Waste vegetable oil

14. Table of Conversion Factors

Land Area	1 Acre = 0.405 Hectares 1 Hectare = $10,000$ m ²
Pressure	1 Atmosphere = 1.013 Bar 1 Atmosphere = .1013 MPa 1 Atmosphere = 14.7 PSI
Mass	1 Metric Tonne = 1000 kg = 2205 lb 1 U.S. Ton = .908 Metric Tonnes 1 lb. = .454 kg
Biomass Production	1 U.S. ton/acre = 2.47 U.S. tons/hectare 1 U.S. ton/acre = 2.24 Metric Tonnes/hectare
Volume	1 U.S. Gal. (liquid) = 3.785 Liters = 0.833 Imperial Gal. 1 m ³ = 264.172 U.S. Gallon (liquid)
Energy	1 kcal = 4.187 kJ 1 BTU = 1.055 kJ 1 BTU/lb. = 2.326 kJ/kg 1 BTU/Gal. = 0.279 kJ/L 1 Quad = 10 ¹⁵ BTU = 1.055 Exajoules
Power	1.0 Watt = 1.0 joule/sec = 3.413 BTU/hr 1.0 KW = 3413 BTU/hr = 1.341 horsepower 1.0 KW-hr = 3.6 MJ = 3413 BTU
Fuel Energy (Approximate, based on LHV)	1 Gal Gasoline = 115,000 BTU = 121 MJ 1 Gal Petroleum Diesel = 130,500 BTU = 137 MJ 1 Gal Biodiesel = 122,000 BTU = 128 MJ 1 Gal Ethanol = 75,700 BTU = 80 MJ
Other (Approximate)	1 Metric Tonne Biodiesel = 300 U.S. Gallon 100 U.S. Gal. Biodiesel/acre = 0.33 tonnes/acre

Appendices

Appendix I. Glossary of Fuel Terms

1 st Generation Biofuels	Fuels produced from commonly available, edible food feedstocks via fermentation (such as grain to ethanol) or transesterification (such as vegetable oil to biodiesel).
2 nd Generation Biofuels	Biofuels produced from non-food feedstocks (such as jatropha, algae, and lignocellulose) by any processing technology, or from edible feedstocks using advanced conversion processes (such as catalytic hydroprocessing).
Advanced Biofuel	Renewable fuel (other than ethanol from grain) that is derived from renewable biomass – particularly from lignocellulosic material.
Algal Fuel	Subset of biofuels, produced from algal lipids. Biodiesel is most common, but could also include renewable diesel.
Alternative Fuel	Any fuel produced from non-petroleum sources. Includes biofuels as well as liquid fuels produced from coal and natural gas.
Biodiesel	Fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oil or animal fats.
Biodistillate	Any mid-distillate fuel (diesel fuel, kerosene, jet fuel, or heating oil) produced from recently living plant or animal materials by a variety of processing technologies.
Biofuel	Fuel produced from recently living plants or animals. This includes gases, liquids, and solids produced via fermentation, digestion, enzymatic hydrolysis, thermal conversion, and other processes.
Biogas	Gas produced by biological breakdown of organic matter in the absence of oxygen. Generally arising from landfills or digestion of sewage material.
Biomass	Living or recently dead lignocellulosic plant matter that can be used as a fuel or fuel feedstock.
Brown Grease	Animal fats and vegetable oils recovered in "grease traps" installed in restaurants and other food processing facilities.
Cellulosic Fuel	Subset of biofuel, produced from lignocellulosic feedstocks.
Cetane Number	A measure of the ignition quality of a fuel based upon ignition delay in a compression ignition engine. The higher the cetane number, the shorter the ignition delay, and the better the ignition quality.
Clean Fuels	Ill-defined, colloquial term having variable meanings. Often used in regulatory language to distinguish from conventional fuels.
Cloud Point	Temperature at which a fuel sample first shows a cloud or haze of crystals when it is cooled under standard test conditions as defined in ASTM D2500.
Conventional Biofuel	Ethanol produced via fermentation of sugars derived from corn, sugar cane, or other edible feedstock.
Conventional Fuels	Any fuel produced from petroleum sources.
Energy Content	The heat produced by combustion of a specified volume or mass of a fuel; also known as heating value. Commonly expressed as BTU/lb. or BTU/gal.
Fatty Acids	Any of the saturated or unsaturated mono-carboxylic acids that occur naturally in the form of mono-, di-, or tri-acylglycerides in animal fats and vegetable oils.
Fatty Acid Methyl Ester (FAME)	Mono-alkyl esters of long-chain fatty acids derived from reaction of animal fats or vegetable oils with methanol.
Fischer-Tropsch Diesel	Diesel fuel produced via gasification of organic feedstocks, followed by Fischer-Tropsch process to convert synthesis gas into non-aromatic, liquid hydrocarbons.

Glossary of Fuel Terms (cont.)

Fossil Fuel	Fuel produced from fossil resources – including coal, petroleum, and natural gas.
Gasification	Process involving high temperature thermal reaction of carbonaceous materials under reduced oxygen conditions to produce synthesis gas (mainly CO and H_2)
Glycerol (Glycerine)	By-product of biodiesel synthesis, arising from transesterification reaction of triglyceride feedstocks.
Green Diesel	Non-fossil hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats. Synonymous with Renewable Diesel.
Hydroprocessing	Range of refinery processes involving catalytic treatment of feedstocks in the presence of hydrogen.
Lipids	Fat-soluble naturally-occurring molecules within cells. Lipids include glycerides (mono-, di-, and tri-), oils, waxes, sterols, phospholipids, and others.
Oxygenate	A fuel component that contains appreciable levels of oxygen; for example, ethanol and biodiesel.
Pour Point	The lowest temperature at which a fuel will just flow when tested under standard conditions as defined in ASTM D97.
Pyrolysis	Process involving moderate temperature thermal reaction of carbonaceous materials under oxygen-free conditions to produce pyrolysis oil, gases, and char.
Pyrolysis Oil	Liquid produced via thermal treatment of organic solids in the absence of oxygen. With cellulosic feedstocks, the resulting oils are highly oxygenated.
Rancimat Test	Oxidative stability test procedure (EN14112) applied to biodiesel fuel. Based upon detection of secondary oxidation products from reaction of biodiesel with oxygen at elevated temperature.
Renewable Diesel	Non-fossil hydrocarbon fuel produced by catalytic hydroprocessing of triglycerides from vegetable oils or animal fats. Synonymous with Green Diesel.
Renewable Fuel	Gas, liquid, or solid fuel produced from modern biologic feedstocks (plants and animals) that can be replenished.
Synthesis Gas (syngas)	Principally carbon monoxide and hydrogen, produced via high temperature treatment of organic material from fossil or renewable sources.
Synthetic Fuel	Liquid fuel, produced from non-petroleum resources, generally via gasification and subsequent reaction of the synthesis gas.
Thermal Depolymerization	Process involving heat and pressure to decompose long-chain organic polymer structures into shorter-chain hydrocarbons that are useful as fuels or chemicals.
Transesterification	Chemical process involving reaction of triglycerides with an alcohol (usually methanol) to produce biodiesel and glycerol.
Triacylglycerides (also called triglycerides)	Chemical constituents of animal fats and vegetable oils. Consist of fatty acid esters of glycerol.
Viscosity	A measure of the resistance to flow of a liquid.
Yellow Grease	Recovered vegetable oil and animal fats that have been used in cooking operations. Also called used cooking oil.

Appendix II. Biodistillate Bibliography

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Brito, A., Borges, M. E., Arvelo, R., Garcia, F., Diaz, M. C., and Otero, N., "Reuse of fried oil to obtain biodiesel: Zeolites Y as a catalyst," <i>International Journal of Chemical Reactor Engineering</i> , Vol. 5, 2007.	Journal	2007		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Cheng, Z. Y.; Xing, J.; Li, S. Y.; Li, L. Thermodynamics calculation of the pyrolysis of vegetable oils. Energy Sources 2004, 26 (9), 849-856.	Journal	2004		х	x					
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Cunningham, J., "Greener than green - Analysis of the lifecycle of biodiesel from farmer's field to pump reveals a startling reduction in overall carbon emissions compared to regular fuel," <i>Professional Engineering</i> , Vol. 20, No. 11, 2007, pp. 42.	Journal	2007						х		
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Demirbas, A. Studies on cottonseed oil biodiesel prepared in non-catalytic SCF conditions. Bioresource Technology 2008, 99, 1125-1130.	Journal	2008		х	х					
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Demirbas, A.; Dincer, K. Sustainable green diesel: A futuristic view. Energy Sources Part A-Recovery Utilization and Environmental Effects 2008, 30 (13),	Journal	2008	x	x						

Shaded entries indicate critical reference

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Demirbas, A., Alternatives to petroleum diesel fuel, <i>Energy Sources Part B-Economics Planning and Policy</i> , Vol. 2, 2007, pp. 343-351.	Journal	2007		x						x
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Demirbas, A., Progress and recent trends in biofuels. Progress in Energy and Combustion Science 33[1], 1-18. 2007.	Journal	2007		х	x					х
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Dincer, K., "Lower emissions from biodiesel combustion," <i>Energy Sources Part</i> A-Recovery Utilization and Environmental Effects, Vol. 30, No. 10, 2008, pp.	Journal	2008				x				

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Dinh, H. T.; Fraer, R.; Proc, K.; McCormick, R.; Chandler, K.; Buchholz, B. Operating Experience and Teardown Analysis for Engines Operated on Biodiesel Blends (B20). SAE Paper Abstracts for CRC Project AVFL-17 2005, 2005-01-3641.	Paper	2005					х			
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Dorado, M. P., Ballesteros, E., Arnal, J. M., Gomez, J., and Lopez, F. J., "Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil," <i>Fuel</i> , Vol. 82, No. 11, 2003, pp. 1311-1315.	Journal	2003				x	x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Dunn, R. O., "Effect of antioxidants on the oxidative stability of methyl soyate (biodiesel)," <i>Fuel Processing Technology</i> , Vol. 86, No. 10, 2005, pp. 1071-1085.	Journal	2005			x		x			
Dunn, R. O.; Shockley, M. W. Improving the low-temperature flow properties of alternative diesesl fuels: Vegetable oil-derived methyl esters. J. Am. Oil Chem. Soc. 1996, 73, 1719-1728.	Journal	1996					x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Encinar, J. M., Gonzalez, J. F., Sabio, E., and Ramiro, M. J., "Preparation and properties of biodiesel from Cynara cardunculus L. oil," <i>Industrial & Engineering Chemistry Research</i> , Vol. 38, No. 8, 1999, pp. 2927-2931.	Journal	1999	х		x					
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Fang,H.L; Alleman,T.L.; McCormick,R.L. "Quantification of Biodiesel Content in Fuels and Lubricants by FTIR and NMR Spectroscopy," <i>SAE International</i> , 2006, 2006-01-3301.	Paper	2006			х		х			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Geller, D. P., Adams, T. T., Goodrum, J. W., and Pendergrass, J., "Storage stability of poultry fat and diesel fuel mixtures: Specific gravity and viscosity," <i>Fuel</i> , Vol. 87, 2008, pp. 92-102.	Journal	2008					x			
Geller, D. P.; Goodrum, J. W. Effects of specific fatty acid methyl esters on diesel fuel lubricity. Fuel 2004, 83 (17-18), 2351-2356.	Journal	2004			x		x			
Geo Varuvel, E. A Comparative Combustion Analysis of Rubber Seed Oil and its Methyl Ester in a D.I. Diesel Engine. SAE International 2008, 2008-01-1386.	Paper	2008				х	х			
Georgogianni, K. G., Kontominas, M. G., Tegou, E., Avlonitis, D., and Gergis, V., "Biodiesel production: Reaction and process parameters of alkali-catalyzed transesterification of waste frying oils," <i>Energy & Fuels</i> , Vol. 21, 2007, pp. 3023-3027.	Journal	2007		x	x					
Georgogianni, K. G.; Kontominas, A. G.; Pomonis, P. J.; Avlonitis, D.; Gergis, V. Alkaline conventional and in situ transesterification of cottonseed oil for the production of biodiesel. Energy & Fuels 2008, 22 (3), 2110-2115.	Journal	2008		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Granados, M. L., Poves, M. D. Z., Alonso, D. M., Mariscal, R., Galisteo, F. C., Moreno-Tost, R., Santamaria, J., and Fierro, J. L. G., "Biodiesel from sunflower oil by using activated calcium oxide," <i>Applied Catalysis B-Environmental</i> , Vol. 73, No. 3-4, 2007, pp. 317-326.	Journal	2007		x						
Granda, C. B., Zhu, L., and Holtzapple, M. T., "Sustainable liquid biofuels and their environmental impact," <i>Environmental Progress</i> , Vol. 26, 2007, pp. 233-250.	Journal	2007								x
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Hanh, H. D.; Dong, N. T.; Starvarache, C.; Okitsu, K.; Maeda, Y.; Nishimura, R. Methanolysis of triolein by low frequency ultrasonic irradiation. Energy Conversion and Management 2008, 49276-280	Journal	2008		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Hess, M. A., Haas, M. J., Foglia, T. A., and Marmer, W. N., "Effect of antioxidant addition on NOx emissions from biodiesel," <i>Energy & Fuels</i> , Vol. 19, No. 4, 2005, pp. 1749-1754.	Journal	2005				x				
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Holser, R. A.; Doll, K. M.; Erhan, S. Z. Metathesis of methyl soyate with ruthenium catalysts. Fuel 2006, 85 (3), 393-395.	Journal	2006		x						
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Hou, X. L., Qi, Y. Q., Qiao, X. G., Wang, G. F., Qin, Z. F., and Wang, J. G., "Lewis acid-catalyzed transesterification and esterification of high free fatty acid oil in subcritical methanol," <i>Korean Journal of Chemical Engineering</i> , Vol. 24, No. 2, 2007, pp. 311-313.	Journal	2007		x						
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Hoydonckx, H. E.; De Vos, D. E.; Chavan, S. A.; Jacobs, P. A. Esterification and transesterification of renewable chemicals. Topics in Catalysis 2004, 27 (1-4),	Journal	2004		х						
Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Huber, G. W., O'Connor, P., and Corma, A., "Processing biomass in conventional oil refineries: Production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures," <i>Applied Catalysis A-General</i> , Vol. 329, 2007, pp. 120-129.	Journal	2007		x	x					
Huber, G. W.; Iborra, S.; Corma, A. Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysts, and Engineering. Chem. Rev. 2006, 106, 4044- 4098.	Journal	2006		x	x					
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Ilkilic, C. The effect of sunflower oil methyl ester and diesel fuel blend on the performance of a diesel engine. Energy Sources Part A-Recovery Utilization and Environmental Effects 2008, 30 (19), 1761-1770.	Journal	2008				x	x			
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India Bio-Fuels Annual 2007;GAIN Report Number IN7047; USDA Foreign Agricultural Service: Jun 1, 07.	Report	2007								x
IPCC IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 4: Agriculture, Forestry, and Other Land Use; 06.	Journal	2006	х					x		

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Johnson, D. T. and Taconi, K. A., "The glycerin glut: Options for the value- added conversion of crude glycerol resulting from biodiesel production," <i>Environmental Progress</i> , Vol. 26, 2007, pp. 338-348.	Journal	2007		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Kass, M. D.; Swartz, M. M.; Lewis, S. A.; Huff, S. P.; Lee, D.; Wagner, R. M.; Storey, J. M. Lowering NOx and PM Emissions in a Light-Duty Diesel Engine with Biodiesel-Water Emulsion, ASABE Meeting, Portland, OR, July 2006.	Conf. Proceed	2006				x	x			
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Kaul, S., Saxena, R. C., Kumar, A., Negi, M. S., Bhatnagar, A. K., Goyal, H. B., and Gupta, A. K., "Corrosion behavior of biodiesel from seed oils of Indian origin on diesel engine parts," <i>Fuel Processing Technology</i> , Vol. 88, No. 3, 2007, pp. 303-307.	Journal	2007			x		х			
Kaushik, N., Kumar, K., and Kumar, S., "Potential of Jatropha curcas for biofuels," <i>Journal of Biobased Materials and Bioenergy</i> , Vol. 1, 2007, pp. 301-314.	Journal	2007		х						
Kawano, D.; Ishii, H.; Goto, Y.; Noda, A. Optimization of Engine System for Application of Biodiesel Fuel. SAE International 2007, JSAE 20077256 (SAE 2007-01-2028), 1254-1260.	Paper	2007				x	x			
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Kegl, B., "Experimental investigation of optimal timing of the diesel engine injection pump using biodiesel fuel," <i>Energy & Fuels</i> , Vol. 20, No. 4, 2006, pp. 1460-1470.	Journal	2006				x				
Kegl, B., "NOx and particulate matter (PM) emissions reduction potential by biodiesel usage," <i>Energy & Fuels</i> , Vol. 21, 2007, pp. 3310-3316.	Journal	2007				x	x			
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Kegl, B., Keg, M., and Pehan, S., "Optimization of a fuel injection system for diesel and biodiesel usage," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1046-1054.	Journal	2008					x			
Kegl, B.; Pehan, S. Influence of biodiesel on injection, fuel spray, and engine characteristics. Thermal Science 2008, 12 (2), 171-182.	Journal	2008				х	x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Kerschbaum, S. and Rinke, G., "Measurement of the temperature dependent viscosity of biodiesel fuels," <i>Fuel</i> , Vol. 83, No. 3, 2004, pp. 287-291.	Journal	2004			x		x			
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Keskin, A., Guru, M., Altiparmak, D., and Aydin, K., "Using of cotton oil soapstock biodiesel-diesel fuel blends as an alternative diesel fuel," <i>Renewable Energy</i> , Vol. 33, 2008, pp. 553-557.	Journal	2008	х				х			
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Khan, M. I., Chhetri, A. B., and Islam, M. R., "Analyzing sustainability of community-based energy technologies," <i>Energy Sources Part B-Economics Planning and Policy</i> , Vol. 2, 2007, pp. 403-419.	Journal	2007								x
Kim, H. J., Kang, B. S., Kim, M. J., Park, Y. M., Kim, D. K., Lee, J. S., and Lee, K. Y., "Transesterification of vegetable oil to biodiesel using heterogeneous base catalyst," <i>Catalysis Today</i> , Vol. 93-5, 2004, pp. 315-320.	Journal	2004		x						
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Kim, M. Y., Yoon, S. H., and Lee, C. S., "Impact of split injection strategy on the exhaust emissions and soot particulates from a compression ignition engine fueled with neat biodiesel," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1260-1265.	Journal	2008				х				
Kim, M. Y.; Yoon, S. H.; Hwang, J. W.; Lee, C. S. Characteristics of Particulate Emissions of Compression Ignition Engine Fueled With Biodiesel Derived From Soybean. ASME Internal Combustion Engine Division 2007 Fall Tech. Conf. 2007, ICEF2007-1715, 1-7.	Journal	2008				x				
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Kinney, A. J. and Clemente, T. E., "Modifying soybean oil for enhanced performance in biodiesel blends," <i>Fuel Processing Technology</i> , Vol. 86, No. 10, 2005, pp. 1137-1147.	Journal	2005			x		x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Kiss, A. A., Dimian, A. C., and Rothenberg, G., "Biodiesel by catalytic reactive distillation powered by metal oxides," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 598-604.	Journal	2008		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Lopez, D. E., Goodwin, J. G., Bruce, D. A., and Lotero, E., "Transesterification of triacetin with methanol on solid acid and base catalysts," <i>Applied Catalysis A-General</i> , Vol. 295, No. 2, 2005, pp. 97-105.	Journal	2005		x						
Lopez, D. E., Suwannakarn, K., Bruce, D. A., and Goodwin, J. G., "Esterification and transesterification on tungstated zirconia: Effect of calcination temperature," <i>Journal of Catalysis</i> , Vol. 247, No. 1, 2007, pp. 43-50.	Journal	2007		x						
Lotero, E., Liu, Y. J., Lopez, D. E., Suwannakarn, K., Bruce, D. A., and Goodwin, J. G., "Synthesis of biodiesel via acid catalysis," <i>Industrial & Engineering Chemistry Research</i> , Vol. 44, No. 14, 2005, pp. 5353-5363.	Journal	2005		x						
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Lu, X. C., Ma, J. J., Ji, L. B., and Huang, Z., "Experimental study on the combustion characteristics and emissions of biodiesel fueled compression ignition engines with premixed dimethoxymethane," <i>Energy & Fuels</i> , Vol. 21, 2007, pp. 3144-3150.	Journal	2007				х	х			
Lu, X. C.; Ma, J. J.; Ji, L. B.; Huang, Z. Simultaneous reduction of NOx emission and smoke opacity of biodiesel-fueled engines by port injection of ethanol. Fuel 2008, 87 (7), 1289-1296.	Journal	2008				x				
Ma, F. R. and Hanna, M. A., "Biodiesel production: a review," <i>Bioresource Technology</i> , Vol. 70, No. 1, 1999, pp. 1-15.	Journal	1999		x	x					
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MacLean, H. Sensitivity analysis of biodiesel LCA models to determine assumptions with the greatest influence on outputs; Cheminfo Services Inc.: Mar 24, 08.	Report	2008						x		
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Madras, G., Kolluru, C., and Kumar, R., "Synthesis of biodiesel in supercritical fluids," <i>Fuel</i> , Vol. 83, No. 14-15, 2004, pp. 2029-2033.	Journal	2004		x						

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Marchetti, J. M., Miguel, V. U., and Errazu, A. F., "Heterogeneous esterification of oil with high amount of free fatty acids," <i>Fuel</i> , Vol. 86, No. 5-6, 2007, pp. 906-910.	Journal	2007		x						
Marchetti, J. M.; Errazu, A. F. Comparison of different heterogeneous catalysts and different alcohols for the esterification reaction of oleic acid. Fuel 2008, 87 (15-16), 3477-3480.	Journal	2008		x						
Marchetti, J. M.; Errazu, A. F. Esterification of free fatty acids using sulfuric acid as catalyst in the presence of triglycerides. Biomass & Bioenergy 2008, 32 (9), 892-895.	Journal	2008		x						
Marchetti, J. M.; Miguel, V. U.; Errazu, A. F. Techno-economic study of different alternatives for biodiesel production. Fuel Processing Technology 2008, 89 (8), 740-748.	Journal	2008		x					x	x
Margaroni, D., "Fuel lubricity," <i>Industrial Lubrication and Tribology</i> , Vol. 50, No. 3, 1998, pp. 108.	Journal	1998			x		x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Mazzoleni, C.; Kuhns, H. D.; Moosmüller, H.; Witt, J.; Nussbaum, N. J.; Chang, MC. O.; Parthasarathy, G.; Kumar, S.; Nathagoundenpalayam, K.; Nikolich, G.; Watson, J. G. A case study of real-world tailpipe emissions for school buses using a 20% biodiesel blend. Science of the Total Environment 385, 146-159. 2007.	Journal	2007				x				
Mbaraka, I. K. and Shanks, B. H., "Design of multifunctionalized mesoporous silicas for esterification of fatty acid," <i>Journal of Catalysis</i> , Vol. 229, No. 2, 2005, pp. 365-373.	Journal	2005		x						
Mbaraka, I. K.; Radu, D. R.; Lin, V. S. Y.; Shanks, B. H. Organosulfonic acid- functionalized mesoporous silicas for the esterification of fatty acid. <i>Journal of</i> <i>Catalysis</i> 2003, 219 (2), 329-336.	Journal	2003		x						
Mbarawa, M. Performance, emission and economic assessment of clove stem oil-diesel blended fuels as alternative fuels for diesel engines. Renewable Energy 2008, 33 (5), 871-882.	Journal	2008	x			x	x	x	x	
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McCormick, R. L.; Alleman, T. L.; Ratcliff, M.; Moens, L.; Lawrence, R. Survey of the Quality and Stability of Biodiesel and Biodiesel Blends in the United States in 2004;NREL/TP-540-38836; Oct, 05.	Report	2005			х					
McCormick, R. L.; Alleman, T. L.; Waynick, J. A.; Westbrook, S. R.; Porter, S. Stability of Biodiesel and Biodiesel Blends: Interim Report;NREL/TP-540-39721; Apr 2, 2003	Paper	2003		х	х	х	х			
McCormick, R. L.; Alvarez, J. R.; Graboski, M. S.; Tyson, K. S.; Vertin, K. Fuel Additive and Blending Approaches to Reducing NOx Emissions from Biodiesel. SAE Technical Paper Series 2002, 2002-01-1658.	Paper	2002			x	x	x			
McCormick, R. L.; Ratcliff, M.; Moens, L.; Lawrence, R. Several Factors affecting the stability of biodiesel in standard accelerated tests. Fuel Processing Technology 2007, 88, 651-657.	Journal	2007			х		x			
McCormick, R. L.; Westbrook, S. R. Empirical Study of the Stability of Biodiesel and Biodiesel Blends; NREL/TP-540-41619; May, 07.	Report	2007			х		х			
McCormick, R. L.; Williams, A.; Ireland, J.; Brimhall, M.; Hayes, R. R. Effects of Biodiesel Blends on Vehicle Emissions;NREL/MP-540-40554; Oct 1, 2006.	Report	2006				х	х			
McCormick, R. L.; Williams, A.; Ireland, J.; Knoll, K.; Yanowitz, J. Overview of Recent Emission Testing Results for Biodiesel and E85. 9-27-2007. 23rd Annual Clean Air Conference.	Slide	2007				x				
McCormick, R.; Alleman, T. L.; Barnitt, R.; Clark, W.; Hayes, B.; Ireland, J.; Ken, P.; Ratcliff, M.; Thornton, M.; Whitacre, S. D.; Williams, A.; Smith, D. Biodiesel R&D at NREL. 2-6-2006. NREL/PR-540-39538.	Slides	2006			x	x	x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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McNeff, C. V.; McNeff, L. C.; Yan, B.; Nowlan, D. T.; Rasmussen, M.; Gyberg, A. E.; Krohn, B. J.; Fedie, R. L.; Hoye, T. R. A continuous catalytic system for biodiesel production. Applied Catalysis A-General 2008, 343 (1-2), 39-48	Journal	2008		x						
Me, W. L., Peng, H., and Chen, L. G., "Calcined Mg-Al hydrotalcites as solid base catalysts for methanolysis of soybean oil," <i>Journal of Molecular Catalysis A-Chemical</i> , Vol. 246, No. 1-2, 2006, pp. 24-32.	Journal	2006		x						
Meher, L. C., Sagar, D. V., and Naik, S. N., "Technical aspects of biodiesel production by transesterification-a review.," <i>Renewable & Sustainable Energy Reviews</i> , Vol. 10, 2006, pp. 248-268.	Journal	2006		x	x					
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Meneghetti, S. A. P., Meneghetti, M. R., Serra, T. A., Barbosa, D. C., and Wolf, C. R., "Biodiesel production from vegetable oil mixtures: cottonseed, soybean, and castor oils," <i>Energy & Fuels</i> , Vol. 21, 2007, pp. 3746-3747.	Journal	2007		x						
Meneghetti, S. M. P., Meneghetti, M. R., Wolf, C. R., Silva, E. C., Lima, G. E. S., Silva, L. D., Serra, T. M., Cauduro, F., and de Oliveira, L. G., "Biodiesel from castor oil: A comparison of ethanolysis versus methanolysis," <i>Energy & Fuels</i> , Vol. 20, No. 5, 2006, pp. 2262-2265.	Journal	2006		x	x					
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Minami, E. and Saka, S., "Kinetics of hydrolysis and methyl esterification for biodiesel production in two-step supercritical methanol process," <i>Fuel</i> , Vol. 85, No. 17-18, 2006, pp. 2479-2483.	Journal	2006		x						
Mitchell, K. Diesel Fuel Lubricity - Base Fuel Effects. SAE Technical Paper Series 2001, 2001-01-1928.	Paper	2001			х		x			
Miyata, I.; Takei, Y.; Okada, M.; Tsurutani, K. Effects of Bio-Fuels on Vehicle Performance: Degradation Mechanism Anaylsys of Bio-Fuels. SAE International 2004, 2004-01-3031.	Paper	2004			х		х			
Mo, X. H.; Lotero, E.; Lu, C. Q.; Liu, Y. J.; Goodwin, J. G. A novel sulfonated carbon composite solid acid catalyst for biodiesel synthesis. Catalysis Let. 2008, 123 (1-2), 1-6.	Journal	2008		x						
Moraes, M. S. A.; Krause, L. C.; da Cunha, M. E.; Faccini, C. S.; de Menezes, E. W.; Veses, R. C.; Rodrigues, M. R. A.; Caramao, E. B. Tallow biodiesel: Properties evaluation and consumption tests in a diesel engine. Energy & Fuels 2008, 22 (3), 1949-1954.	Journal	2008			x	x	x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Moreira, A. B. R., Perez, V. H., Zanin, G. M., and de Castro, H. F., "Biodiesel synthesis by enzymatic transesterification of palm oil with ethanol using lipases from several sources immobilized on silica-PVA composite," <i>Energy & Fuels</i> , Vol. 21, 2007, pp. 3689-3694.	Journal	2007		x						
Morgenstern, M., Cline, J., Meyer, S., and Cataldo, S., "Determination of the kinetics of biodiesel production using proton nuclear magnetic resonance spectroscopy (H-1 NMR)," <i>Energy & Fuels</i> , Vol. 20, No. 4, 2006, pp. 1350-1353.	Journal	2006		×						
Morin, P.; Hamad, B.; Sapaly, G.; Rocha, M. G. C.; de Oliveira, P. G. P.; Gonzalez, W. A.; Sales, E. A.; Essayem, N. Transesterification of rapeseed oil with ethanol I. Catalysis with homogeneous Keggin heteropolyacids. Applied Catalysis A-General 2007, 330, 69-76.	Journal	2007		x						
Morino, T.; Morimune, T. Diesel Engin Operation and Exhaust Emissions when Fueled with Animal Fats. SAE International 2005, 2005-01-3673.	Paper	2005				x				
Moron-Villarreyes, J. A., Soldi, C., Amorim, A. M., Pizzolatti, M. G., Mendonca, A. P., and D'Oca, M. G. M., "Diesel/biodiesel proportion for by-compression ignition engines," <i>Fuel</i> , Vol. 86, No. 12-13, 2007, pp. 1977-1982.	Journal	2007			x		х			
Moser, B. R., Cermak, S. C., and Isbell, T. A., "Evaluation of castor and lesquerella oil derivatives as additives in biodiesel and ultralow sulfur diesel fuels," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1349-1352.	Journal	2008					х			
Mosey, G.; Kreycik, C. State Clean Energy Practices: Renewable Fuel Standards;NREL/TP-670-43513; Jul, 2008.	Report	2008								x
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Muncrief, R. L., Rooks, C. W., Cruz, M., and Harold, M. P., "Combining biodiesel and exhaust gas recirculation for reduction in NOx and particulate emissions," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1285-1296.	Journal	2008				x				
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Mushrush, G. W., Beal, E. J., Hughes, J. M., Wynne, J. H., Sakran, J. V., and Hardy, D. R., "Biodiesel fuels: Use of soy oil as a blending stock for middle distillate petroleum fuels," <i>Industrial & Engineering Chemistry Res.</i> , Vol. 39, No. 10, 2000, pp. 3945-3948.	Journal	2000			x		x			
Mushrush, G. W., Mose, D. G., Wray, C. L., and Sullivan, K. T., "Biofuels as a means of improving the quality of petroleum middle distillate fuels," <i>Energy Sources</i> , Vol. 23, No. 7, 2001, pp. 649-655.	Journal	2001			x		x			
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Mushrush, G. W., Wynne, J. H., Lloyd, C. T., Willauer, H. D., and Beal, E. J., "Soybean biodiesel: Instability reactions," <i>Petroleum Sci. and Technol.</i> , Vol. 25, 2007, pp. 1163-1171.	Journal	2007			x		x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Mushrush, G. W., Wynne, J. H., Lloyd, C. T., Willauer, H. D., and Hughes, J. M., "Instability reactions and recycled soybean-derived biodiesel fuel liquids," <i>Energy Sources Part A-Recovery Utilization and Environmental Effects</i> , Vol. 29, No. 5, 2007, pp. 491-497.	Journal	2007					x			
Mushrush, G. W., Wynne, J. H., Willauer, H. D., Lloyd, C. T., Hughes, J. M., and Beal-, E., "Recycled soybean cooking oils as blending stocks for diesel fuels," <i>Industrial & Engineering Chemistry Research</i> , Vol. 43, No. 16, 2004, pp. 4944-4946.	Journal	2004			x					
Myo, T.; Hamasaki, K.; Kinoshita, E.; Tajima, H. Diesel Combustion Characteristics of Single Compositions of Fatty Acid Methyl Esters. SAE International 2005, 2005-32-0042.	Paper	2005			x	x				
Myo, T.; Kinoshita, E.; Tsuru, H.; Hamasaki, K. Combustion Characteristics of a DI Diesel Engine with Palm Kernel Oil Biodiesel and Its Blend (B20). SAE International 2007, JSAE-20076568.	Paper	2007				x	x			
Nadar, K. N., Reddy, R. P., and Anjuri, E. R., "Comparison of performance of biodiesels of mahua oil and gingili oil in dual fuel engine," <i>Thermal Sci.</i> , Vol. 12, No. 1, 2008, pp. 151-156.	Journal	2008	x		x					
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Nakajima, K.; Haraw, M.; Hayashi, S. Environmentally benign production of chemicals and energy using a carbon-based strong solid acid. Journal of the American Ceramic Society 2007, 90, 3725-3734.	Paper	2007				x	x			
Narasimharao, K., Brown, D. R., Lee, A. F., Newman, A. D., Siril, P. F., Tavener, S. J., and Wilson, K., "Structure-activity relations in Cs-doped heteropolyacid catalysts for biodiesel production," <i>Journal of Catalysis</i> , Vol. 248, No. 2, 2007, pp. 226-234.	Journal	2007		х						
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Nas, B. and Berktay, A., "Energy potential of biodiesel generated from waste cooking oil: An environmental approach," <i>Energy Sources Part B-Economics Planning and Policy</i> , Vol. 2, 2007, pp. 63-71.	Journal	2007							х	x
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Nast, M., Langniss, O., and Leprich, U., "Instruments to promote renewable energy in the German heat market - Renewable Heat Sources Act," <i>Renewable Energy</i> . Vol. 32, No. 7, 2007, pp. 1127-1135.	Journal	2007								x

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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National Renewable Energy Laboratory, Biodiesel Handling and Use Guide, Report NREL/TP-540-43672, January 2009	Report	2009			x		х			
Neto, B. A. D., Alves, M. B., Lapis, A. A. M., Nachtigall, F. M., Eberlin, M. N., Dupont, J., and Suarez, P. A. Z., "1-n-Butyl-3-methylimidazolium tetrachloro- indate (BMI center dot InCl4) as a media for the synthesis of biodiesel from vegetable oils," <i>Journal of Catalysis</i> , Vol. 249, 2007, pp. 154-161.	Journal	2007		x						
Neumann, A.; Jebens, T.; Wierzbicki, V. A Method for Determining Oxidation Stability of Petrodiesel, Biodiesel, and Blended Fuels. American Laboratory 2008, 40 (4), 22.	Report	2008					х			
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Ngo, H. L., Zafiropoulos, N. A., Foglia, T. A., Samulski, E. T., and Lin, W. B., "Efficient two-step synthesis of biodiesel from greases," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 626-634.	Journal	2008		x						
Ni, J. and Meunier, F. C., "Esterification of free fatty acids in sunflower oil over solid acid catalysts using batch and fixed bed-reactors," <i>Applied Catalysis A-General</i> , Vol. 333, 2007, pp. 122-130.	Journal	2007		x						
Niederl, A. and Narodoslawsky, M., "Ecological evaluation of processes based on by-products or waste from agriculture: Life cycle assessment of biodiesel from tallow and used vegetable oil," <i>Feedstocks for the Future: Renewables for</i> <i>the Production of Chemicals and Materials</i> , Vol. 921, 2006, pp. 239-252.	Book Chapter	2006						x		
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Nikiema, J.; Heitz, M. Biodiesel. I Characteristics, assets and limits - a summarization. Canadian Journal of Civil Engineering 2008, 1, 95-106.	Journal	2008			х	x	x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Ozsezen, A. N., Canakci, M., and Sayin, C., "Effects of biodiesel from used frying palm oil on the performance, injection, and combustion characteristics of an indirect injection diesel engine," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1297-1305.	Journal	2008					x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Ramadhas, A. S.; Muraleedharan, C.; Jayaraj, S. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. <i>Renewable Energy</i> 2005, 30 (12), 1789-1800	Journal	2005		x	х	x				
Ranganathan, S. V.; Narasimhan, S. L.; Muthukumar, K. An overview of enzymatic production of biodiesel. <i>Bioresource Technology</i> 2008, 99 (10), 3975-3981.	Journal	2008		x						
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Serdari, A., Fragioudakis, K., Kalligeros, S., Stournas, S., and Lois, E., "Impact of using biodiesels of different origin and additives on the performance of a stationary diesel engine," <i>Journal of Engineering for Gas Turbines and Power-Transactions of the Asme</i> , Vol. 122, No. 4, 2000, pp. 624-631.	Journal	2000				х	x			
Serdari, A., Fragioudakis, K., Teas, C., Sakellaropoulos, F., Zannikos, F., Stournas, S., and Lois, E., "Adding biodiesel corn oil and sunflower oil to diesel fuel: the impact on the performance of conventional road vehicles," <i>Journal of</i> <i>the Institute of Energy</i> , Vol. 71, No. 488, 1998, pp. 126-136.	Journal	1998				х	х			
Serdari, A., Fragioudakis, K., Teas, C., Zannikos, F., Stournas, S., and Lois, E., "Effect of biodiesel addition to diesel fuel on engine performance and emissions," <i>Journal of Propulsion and Power</i> , Vol. 15, No. 2, 1999, pp. 224-231.	Journal	1999			х		x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Shaine Tyson, K.; Bozell, J.; Wallace, R.; Petersen, E.; Moens, L. Biomass Oil Analysis: Research Needs and Recommendations;NREL/TP-510-34976; NREL, Jun 1, 2004.	Report	2004		x	х			x	x	
Sharma, Y. C. and Singh, B., "Development of biodiesel from karanja, a tree found in rural India," <i>Fuel</i> , Vol. 87, No. 8-9, 2008, pp. 1740-1742.	Journal	2008	x		x					
Sharma, Y. C.; Singh, B.; Upadhyay, S. N. Advancements in development and characterization of biodiesel: A review. Fuel 2008, 87 (12), 2355-2373.	Journal	2008		x		x	x			
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Sinha, S. and Agarwal, A. K., "Experimental investigation of the combustion characteristics of a biodiesel (rice-bran oil methyl ester)-fuelled direct-injection transportation diesel engine," <i>Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering</i> , Vol. 221, 2007, pp. 921-932.	Journal	2007			x	x				
Sinha, S.; Agarwai, A. K. Ricebran Oil Biodiesel's Performance, Emission and Endurance Test on a CIDI Transport Engine. SAE International 2008, 2008-28- 0066.	Paper	2008				x	x			
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Sinha, S.; Agarwal, A. K.; Garg, S. Biodiesel development from rice bran oil: Transesterification process optimization and fuel characterization. Energy Conversion and Management 2008, 49 (5), 1248-1257.	Journal	2008		x	x					
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Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Song, J. H., Alam, M., Boehman, A. L., and Kim, U., "Examination of the oxidation behavior of biodiesel soot," <i>Combustion and Flame</i> , Vol. 146, No. 4, 2006, pp. 589-604.	Journal	2006				x				
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Sorichetti, P. A.; Romano, S. D. Physico-chemical and electrical properties for the production and characterization of Biodiesel. <i>Physics and Chem. of Liquids</i> 2005, 43 (1), 37-48.	Journal	2005		x	х					
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Spessert, B. M.; Arendt, I.; Schleicher, A. Influence of RME and Vegetable Oils on Exhaust Gas and Noise Emissions of Small Industrial Diesel Engines. SAE International 2004, 2004-32-0070.	Paper	2004				x	x			
Sreeprasanth, P. S., Srivastava, R., Srinivas, D., and Ratnasamy, P., "Hydrophobic, solid acid catalysts for production of biofuels and lubricants," <i>Applied Catalysis A-General</i> , Vol. 314, No. 2, 2006, pp. 148-159.	Journal	2006		x						
Srivastava, A. and Prasad, R., "Triglycerides-based diesel fuels," <i>Renewable</i> & Sustainable Energy Reviews, Vol. 4, No. 2, 2000, pp. 111-133.	Journal	2000			х	x	x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Srivastava, P. K. and Verma, M., "Methyl ester of karanja oil as an alternative renewable source energy," <i>Fuel</i> , Vol. 87, No. 8-9, 2008, pp. 1673-1677.	Journal	2008	x		х	х				
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Standard Specification for Diesel Fuel Oil, Biodiesel Blend (B6 to B20);D7467 - 08; ASTM: Oct 13, 2008.	Report	2008			х					
Standard Specification for Diesel Fuel Oils;D975-08a; ASTM: Oct 13, 2008.	Report	2008			х					
Stavarache, C.; Vinatoru, M.; Maeda, Y. Aspects of ultrasonically assisted transesterification of various vegetable oils with methanol. Ultrasonics Sonochemistry 2007, 14 (3), 380-386.	Journal	2007		x						
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Su, C. H., Fu, C. C., Gomes, J., Chu, I. M., and Wu, W. T., "A heterogeneous acid-catalyzed process for biodiesel production from enzyme hydrolyzed fatty acids," <i>AICHE Journal</i> , Vol. 54, 2008, pp. 327-336.	Journal	2008		x						
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Sug, H. K., Park, S. H., and Lee, C. S., "Experimental investigation of nozzle cavitating flow characteristics for diesel and biodiesel fuels," <i>International Journal of Automotive Technology</i> , Vol. 9, No. 2, 2008, pp. 217-224.	Journal	2008					x			
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Sundarapandian, Devaradjane, Theoretical and Experimental Investigation of the Performance of Vegetable Oil Operated CI Engine. SAE International 2007, JSAE-20076567, SAE 2007-32-0067.	Paper	2007				x	x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Sunita, G.; Devassy, B. M.; Vinu, A.; Sawant, D. P.; Balasubramanian, V. V.; Halligudi, S. B. Synthesis of biodiesel over zirconia-supported isopoly and heteropoly tungstate catalysts. Catalysis Communications 2008, 9 (5), 696-702	Journal	2008		х						
Suppes, G. J.; Dasari, M. A.; Doskocil, E. J.; Mankidy, P. J.; Goff, M. J. Transesterification of soybean oil with zeolite and metal catalysts. Applied Catalysis A-General 2004, 257 (2), 213-223.	Journal	2004		x						
Sureshkumar, K.; Velraj, R.; Ganesan, R. Performance and exhaust emission characteristics of a CI engine fueled with Pongamia pinnata methyl ester (PPME) and its blends with diesel. Renewable Energy 2008, 33 (10), 2294-2302	Journal	2008				x	x			
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Suryanarayanan, S.; Manikandan Janakiraman, V.; Sekar, J.; Lakshmi Narayana Rao, G.; Sampath, S. Determination of the Proportion of Blend of Biodiesel with Diesel for Optimal Engine Performance and Emission Characteristics. SAE International 2006. 2006-01-3534	Paper	2006				х	х			
Suryawanshi, J. G.; Deshpande, N. V. Effect of EGR on Performance and Emissions ina Diesel Engine Fueled with Jatropha Oil Methyl Ester; SAE. 2005- 26-028; 2005.	Paper	2005			x	x				
Suryawanshi, J. G.; Deshpande, N. V. Experimental Investigations on a Pongamia Oil Methyl-Ester-Fuelled Diesel Engine. SAE International 2004.	Journal	2004				x	x			
Suryawanshi, J. G.; Deshpande, N. V. Experimental Investigations on a Pongamia Oil Methyl-Ester-Fuelled Diesel Engine. SAE International 2004. 2004-28-0018	Paper	2004				х				
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Suryawanshi, J. G.; Deshpande, N. V. The Effects of Combination of EGR, Injection Retard and Injection Pressure on Emissions and Performance of Diesel Engine Fuelled With Jatropha Oil Methyl Ester. ASME International Mechanical Engineering Congress and Exposition 2006, IMECE2006-13021, 1- 12.	Paper	2006				x				
Suwannakarn, K.; Lotero, E.; Goodwin, J. G.; Lu, C. Q. Stability of sulfated zirconia and the nature of the catalytically active species in the transesterification of triglycerides. Journal of Catalysis 2008, 255 (2), 279-286.	Journal	2008		x						
Sze, C.; Whinihan, J. K.; Olson, B. A.; Schenk, C. R.; Sobotowski, R. A. Impact of Test Cycle and Biodiesel Concentration on Emissions. SAE 2007 Transactions Journal of Fuels and Lubricants 2007, V116-4 (2007-01-4040).	Paper	2007				x				
Szybist, J. P., Boehman, A. L., Taylor, J. D., and McCormick, R. L., "Evaluation of formulation strategies to eliminate the biodiesel NOx effect," <i>Fuel Processing Technology</i> , Vol. 86, No. 10, 2005, pp. 1109-1126.	Journal	2005				x				

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Szybist, J.; Druckenmiller, M.; Khalid, O.; Boehman, A. L.; Scaroni, A.; Simmons, J. Potential Methods for NOx Reduction From Biodiesel. SAE International 2003.	Paper	2003				x	x			
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Tailleur, R. E. G. and Caris, P. O. C., "Low emission using oxidized diesel," International Journal of Chemical Reactor Engineering, Vol. 5, 2007.	Journal	2007			x	x				
Talukder, M. M. R., Beatrice, K. L. M., Song, O. P., Puah, S., Wu, J. C., Won, C. J., and Chow, Y., "Improved method for efficient production of biodiesel from palm oil," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 141-144.	Journal	2008		х						
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Tate, R. E., Watts, K. C., Allen, C. A. W., and Wilkie, K. L., "The viscosities of three biodiesel fuels at temperatures up to 300 oC," <i>Fuel</i> , Vol. 85, No. 7-8, 2006, pp. 1010-1015.	Journal	2006			x					
Taylor, M.; Whitney, R.; Waller, M. GC-2010 analysis of biodiesel for free and total glycerines by ASTM-6584 with near on-column injection. LC GC North America 2007, 61.	Journal	2007			x					
Terry, B. Impact of Biodiesel on Fuel System Component Durability;NREL/TP- 540-39130; CRC project AVFL-2A; Coordinating Research Council/NREL: Dec, 2005.	Report	2005			x		x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Tesser, R., Di Serio, M., Guida, M., Nastasi, M., and Santacesaria, E., "Kinetics of oleic acid esterification with methanol in the presence of triglycerides," <i>Industrial & Engineering Chemistry Research</i> , Vol. 44, No. 21, 2005, pp. 7978- 7982.	Journal	2005		х						
Tesser, R., Santacesaria, E., Di Serio, M., Di Nuzzi, G., and Fiandra, V., "Kinetics of glycerol chlorination with hydrochloric acid: A new route to alpha,gamma-dichlorohydrin," <i>Industrial & Engineering Chemistry Research</i> , Vol. 46, 2007, pp. 6456-6465.	Journal	2007		x						
Theinnoi, K.; Rounce, P.; Tsolakis, A.; Wyszynski, M.; Xu, H.; York, A. Activity of Prototype Catalysts on Exhaust Emissions From Biodiesel Fuelled Engines. SAE International 2008, 2008-01-2514.	Paper	2008				x				
Thomas, E. W.; Fuller, R. E.; Terauchi, K. Fluoroelastomer Compatibility with Biodiesel Fuels. SAE 2007 Transactions J. of Fuels and Lubricants 2007, V116-4 (2007-01-4061).	Paper	2007					х			
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Ting, W. J.; Huang, C. M.; Giridhar, N.; Wu, W. T. An enzymatic/acid-catalyzed hybrid process for biodiesel production from soybean oil. Journal of the Chinese Institute of Chemical Engineers 2008, 39 (3), 203-210.	Journal	2008		х						
Tippayawong, N.; Kongjareon, E.; Jompakdee, W. Ethanolysis of soybean oil into biodiesel: Process optimization via central composite design. Journal of Mechanical Science and Technology. Vol. 19. pp. 1902-1909. 2005	Journal	2005		х						
Tittabutt, T. and Trakarnpruk, W., "Metal-loaded MgAl oxides for transesterification of glyceryl tributyrate and palm oil," <i>Industrial & Engineering Chemistry Research</i> , Vol. 47, No. 7, 2008, pp. 2176-2181.	Journal	2008		x						
Tomasevic, A. V.; Siler-Marinkovic, S. S. Methanolysis of used frying oil. Fuel Processing Technology 2003, 81 (1), 1-6.	Journal	2003		х						
Trakarnpruk, W.; Porntangjitlikit, S. Palm oil biodiesel synthesized with potassium loaded calcined hydrotalcite and effect of biodiesel blend on elastomer properties. Renewable Energy 2008, 33 (7), 1558-1563.	Journal	2008		x	x					
Tremblay, A. Y.; Cao, P. G.; Dube, M. A. Biodiesel production using ultralow catalyst concentrations. Energy & Fuels 2008, 22 (4), 2748-2755.	Journal	2008		х						
Tsolakis, A., "Effects on particle size distribution from the diesel engine operating on RME-biodiesel with EGR," <i>Energy & Fuels</i> , Vol. 20, No. 4, 2006, pp. 1418-1424.	Journal	2006				х				
Tyson, K. S., "DOE analysis of fuels and coproducts from lipids," <i>Fuel Processing Technology</i> , Vol. 86, No. 10, 2005, pp. 1127-1136.	Journal	2005	x	x					x	
Tyson, K. S.; Bozell, J.; Wallace, R.; Petersen, E.; Moens, L. Biomass Oil Analysis: Research Needs and Recommendations;NREL/TP-510-34976; NREL, Jun 1, 04.	Report	2004			x		x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
U.C.Davis; U.C.Berkeley California Biodiesel Multimedia Evaluation - Tier 1 Report; Dec, 08.	Report	2008						х		x
UK Department of Transport UK Policy, Renewable Transport Fuel Obligation; 05.	Bill	2005								x
U.S.Congress . H.R. 6: Energy Independence and Security Act of 2007. P.L. 110-140. 2007.	Bill	2007								x
U.S.Congress . Energy Policy Act of 2005; Public Law 109-58. 2005.	Bill	2005								x
U.S. DOE - EERE. Straight Vegetable Oil as a Diesel Fuel. April 2006. DOE. Energy Efficiency and Renewable Energy.	Report	2006		x	х		х			
U.S.DOE-EERE, Biodiesel Blends, DOE/GO-102008-2542, April 2008.	Pamphlet	2008			х	х	x			
U.S.DOE-EERE. Biodiesel handling and use guidelines. DOE/GO-102006-2358 (2006).	Report	2006			х		х			
U.S. DOE Genomics: GTL Roadmap;DOE/SC-0090; DOE Office of Science: Aug, 05.	Report	2005	х	x						
U.S. EPA Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use. U. S. Environmental Protection Agency 2007.	Journal	2007						x		
U.S.EPA. A comprehensive analysis of biodiesel impacts on exhaust emissions;EPA420-P-02-001; U.S. Environmental Protection Agency: Ann Arbor, MI, 2002.	Report	2002				x				
Ulusoy, Y., Tekin, Y., Cetinkaya, M., and Karaosmanoglu, F., "The engine tests of biodiesel from used frying oil," <i>Energy Sources</i> , Vol. 26, No. 10, 2004, pp. 927-932.	Journal	2004				х	x			
Utlu, Z.; Kocak, M. S. The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. Renewable Energy 2008, 33 (8), 1936-1941.	Journal	2008			x	x				
Valliyappan, T.; Bakhshi, N. N.; Dalai, A. K. Pyrolysis of glycerol for the production of hydrogen or syn gas. Bioresource Technology 2008, 99 (10), 4476-4483.	Journal	2008		x						
Van Gerpen, J. The Basics of Diesel Engines and Diesel Fuels. In The Biodiesel Handbook, Knothe, G., Van Gerpen, J., Krahl, J., Eds.; AOCS Press, Urbana, IL 61802: 2005; pp 1-3.	Book Chapter	2005					x			
Van Gerpen, J., "Biodiesel processing and production," <i>Fuel Processing Technology</i> , Vol. 86, No. 10, 2005, pp. 1097-1107.	Journal	2005		x	x					
Van Gerpen, J.; Knothe, G. Basics of the Transesterification Reaction. In The Biodiesel Handbook, Knothe, G., Van Gerpen, J., Krahl, J., Eds.; AOCS Press, Urbana, IL 61802: 2005; pp 26-41.	Book Chapter	2005		×						
Van Gerpen, J.; Shanks, B.; Pruszko, R.; Clements, D.; Knothe, G. Biodiesel Production Technologies;NREL/SR-510-36244; DOE: Jan, 2004.	Report	2004	x	x	x					
Van Ginneken, L., Meers, E., Guisson, R., Ruttens, A., Elst, K., Tack, F. M. G., Vangronsveld, J., Diels, L., and Dejonghe, W., "Phytoremediation for heavy metal-contaminated soils combined with bioenergy production," <i>Journal of Environmental Engineering and Landscape Management</i> , Vol. 15, No. 4, 2007, pp. 227-236.	Journal	2007		x						

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Varma, M. N. and Madras, G., "Synthesis of biodiesel from castor oil and linseed oil in supercritical fluids," <i>Industrial & Engineering Chem. Res.</i> , Vol. 46, No. 1, 2007, pp. 1-6.	Journal	2007		x						
Veljkovic, V. B., Lakicevic, S. H., Stamenkovic, O. S., Todorovic, Z. B., and Lazic, M. L., "Biodiesel production from tobacco (Nicotiana tabacum L.) seed oil with a high content of free fatty acids," <i>Fuel</i> , Vol. 85, No. 17-18, 2006, pp. 2671-2675.	Journal	2006	x		x					
Venturi, P.; Venturi, G. Analysis of energy comparison for crops in European agricultural systems. Biomass & Bioenergy 2003, 25, 235-255.	Journal	2006						х		x
Verhaeven, E.; Pelkmans, L.; Govaerts, L.; Lamers, R.; Theunissen, F. Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. SAE International 2005. 2005-01-2201.	Paper	2005				х	х			
Verziu, M., Cojocaru, B., Hu, J. C., Richards, R., Ciuculescu, C., Filip, P., and Parvulescu, V. I., "Sunflower and rapeseed oil transesterification to biodiesel over different nanocrystalline MgO catalysts," <i>Green Chemistry</i> , Vol. 10, No. 4, 2008, pp. 373-381.	Journal	2008		х						
Vicente, G., Martinez, M., and Aracil, J., "A comparative study of vegetable oils for biodiesel production in Spain," <i>Energy & Fuels</i> , Vol. 20, No. 1, 2006, pp. 394-398.	Journal	2006	x		x					
Vicente, G., Martinez, M., Aracil, J., and Esteban, A., "Kinetics of sunflower oil methanolysis," <i>Industrial & Engineering Chemistry Research</i> , Vol. 44, No. 15, 2005, pp. 5447-5454.	Journal	2005		х						
Vicente, G.; Martinez, M.; Aracil, J. Kinetics of Brassica carinata oil methanolysis. Energy & Fuels 2006, 20 (4), 1722-1726.	Journal	2006		х						
Vicente, G.; Martinez, M.; Aracil, J.; Esteban, A. Kinetics of sunflower oil methanolysis. Industrial & Engineering Chemistry Research 2005, 44 (15), 5447-5454.	Journal	2005		х						
Vieitez, I.; da Silva, C.; Borges, G. R.; Corazza, F. C.; Oliveira, J. V.; Grompone, M. A.; Jachmanian, I. Continuous production of soybean biodiesel in supercritical ethanol-water mixtures. Energy & Fuels 2008, 22 (4), 2805-2809.	Journal	2008		х						
Vivek and Gupta, A. K Biodiesel production from Karanja oil. Journal of Scientific & Industrial Research 63[1], 39-47. 2004.	Journal	2004	x	x	x	х				
Wain, K. S., Perez, J. M., Chapman, E., and Boehman, A. L., "Alternative and low sulfur fuel options: boundary lubrication performance and potential problems," <i>Tribology International</i> , Vol. 38, No. 3, 2005, pp. 313-319.	Journal	2005			x	x				
Wang, L. Y.; He, H. Y.; Xie, Z. F.; Yang, J. C.; Zhu, S. L. Transesterification of the crude oil of rapeseed with NaOH in supercritical and subcritical methanol. Fuel Processing Technology 2007, 88 (5), 477-481.	Journal	2007		х						
Wang, L. Y.; Yang, J. C. Transesterification of soybean oil with nano-MgO or not in supercritical and subcritical methanol. Fuel 2007, 86 (3), 328-333.	Journal	2007		x						
Wang, M. Life cycle analysis practicality. 2008.	Journal	2008						х		

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Wang, W. G., Lyons, D. W., Clark, N. N., Gautam, M., and Norton, P. M Emissions from nine heavy trucks fueled by diesel and biodiesel blend without engine modification. Environmental Science & Technology 34[6], 933-939. 2000.	Journal	2000				х				
Wang, Y. D.; Al-Shemmeri, T.; Eames, P.; McMullan, J.; Hewitt, N.; Huang, Y.; Rezvani, S. An experimental investigation of the performance and gaseous exhaust emissions of a diesel engine using blends of a vegetable oil. Applied Thermal Engineering 2006, 26 (14-15), 1684-1691.	Journal	2006				x	x			
Wang, Y., Ou, S. Y., Liu, P. Z., Xue, F., and Tang, S. Z., "Comparison of two different processes to synthesize biodiesel by waste cooking oil," <i>Journal of Molecular Catalysis A-Chemical</i> , Vol. 252, No. 1-2, 2006, pp. 107-112.	Journal	2006		x						
Wang, Y.; Ou, S. Y.; Liu, P. Z.; Zhang, Z. S. Preparation of biodiesel from waste cooking oil via two-step catalyzed process. Energy Conversion and Management 2007, 48 (1), 184-188.	Journal	2007		x						
Wang, Z. M., Lee, J. S., Park, J. Y., Wu, C. Z., and Yuan, Z. H., "Novel biodiesel production technology from soybean soapstock," <i>Korean Journal of Chemical Engineering</i> , Vol. 24, 2007, pp. 1027-1030.	Journal	2007		x	x					
Water Implications of Biofuels Production in the United States; National Academies Press: Washington D.C., 08.	Report	2008						x		
Watkins, R. S., Lee, A. F., and Wilson, K., "Li-CaO catalysed tri-glyceride transesterification for biodiesel applications," <i>Green Chemistry</i> , Vol. 6, No. 7, 2004, pp. 335-340.	Journal	2004		x						
Waynick, J. A. Characterization of Biodiesel Oxidation and Oxidation Products;AVFL-2b/09-10721/Task 1 Results; NREL/SwRI/CRC/The Coordinating Reserach Council: Aug, 2005.	Report	2005			х		x			
Waynick, J. A. Evaluation of the Stability, Lubricity, and cold flow properties of biodiesel fuels, 6th International Conference on Stability and Handling of Liquid Fuels, Vancouver, B.C., October 1997.	Conf. Proceed.	1997			х		x			
Weaver, J.; Higgins, J. Big Win for Biodiesel: ASTM Approves New Biodiesel Blend Specifications. National Biodiesel Board, Jun 20, 2008.	Newspap er	2008								x
Weiksner, J. M.; Crump, S. L.; White, T. L. Understanding Biodiesel Fuel Quality and Performance; 2008. US DOE. DE-AC09-96SR18500	Report	2008		x	x					
Well-to-wheels analysis of future automotive fuels and powertrains in the European context; European Commission; Joint Research Centre: May, 06.	Report	2006		x				x	x	x
West, A. H., Posarac, D., and Ellis, N., "Simulation, case studies and optimization of a biodiesel process with a solid acid catalyst," <i>International Journal of Chemical Reactor Engineering</i> , Vol. 5, 2007.	Journal	2007		x					x	
Westbrook, S. R. An Evaluation and Comparison of Test Methods to Measure the Oxidation Stability of Neat Biodiesel;NREL/SR-540-38983; Nov, 05.	Report	2005			x		х			
Williams, A., McCormick, R.L., Hayes, R.R., Ireland, J., Fang, H.L. Effect of biodiesel blends on diesel particulate filter performance. SAE 2006-01-3280 (2006).	Paper	2006				x	x			
Williams, A.; McCormick, R. L.; Hayes, R.; Ireland, J. Biodiesel Effects on Diesel Particle Filter Performance; NREL/TP-540-39606; Mar, 2006.	Report	2006				x	x			
Reference		Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
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Williamson, A. M. and Badr, O., "Assessing the viability of using rape methyl ester (RME) as an alternative to mineral diesel fuel for powering road vehicles in the UK," <i>Applied Energy</i> , Vol. 59, No. 2-3, 1998, pp. 187-214.	Journal	1998			x	x				x
Wong, A., "Tall Oil-Based Cetane Enhancer for Diesel Fuel," <i>Pulp & Paper-Canada</i> , Vol. 96, No. 11, 1995, pp. 37-40.	Journal	1995	х	х						
Worldwide Fuel Charter: Biodiesel Guidelines;Draft 1st ed.; European Automobile Manufacturer's Association: Jul, 2008.	Report	2008			x					
Worldwide Fuel Charter;4th Edition; European Automobile Manufacturer's Association: Sep, 06.	Report	2006			x					
Wu, Q., Chen, H., Han, M. H., Wang, D. Z., and Wang, J. F., "Transesterification of Cottonseed oil catalyzed by bronsted acidic ionic liquids," <i>Industrial & Engineering Chemistry Research</i> , Vol. 46, 2007, pp. 7955-7960.	Journal	2007		x						
Wu, Y. P. G.; Lin, Y. F.; Chang, C. T. Combustion characteristics of fatty acid methyl esters derived from recycled cooking oil. Fuel 2007, 86, 2810-2816.	Journal	2007			x	х				
Wynne, J. H., Beal, E. J., Lloyd, C. T., Hardy, D. R., Mushrush, G. W., and Hughes, J. M., "Soybean-derived fuel liquids as additives for middle distillate transportation fuels," <i>Energy Sources</i> , Vol. 26, No. 1, 2004, pp. 19-24.	Journal	2004			x					
Xie, W. L. and Huang, X. M., "Synthesis of biodiesel from soybean oil using heterogeneous KF/ZnO catalyst," <i>Catalysis Letters</i> , Vol. 107, No. 1-2, 2006, pp. 53-59.	Journal	2006		x						
Xie, W. L. and Yang, Z. Q., "Ba-ZnO catalysts for soybean oil transesterification," <i>Catalysis Letters</i> , Vol. 117, No. 3-4, 2007, pp. 159-165.	Journal	2007		х						
Xie, W. L., Yang, Z. Q., and Chun, H., "Catalytic properties of lithium-doped ZnO catalysts used for biodiesel preparations," <i>Industrial & Engineering Chemistry Research</i> , Vol. 46, 2007, pp. 7942-7949.	Journal	2007			x		х			
Xie, W. L. and Li, H. T., "Alumina-supported potassium iodide as a heterogeneous catalyst for biodiesel production from soybean oil," <i>Journal of Molecular Catalysis A-Chemical</i> , Vol. 255, No. 1-2, 2006, pp. 1-9.	Journal	2006				x	x			
Xie, W. L., Peng, H., and Chen, L. G., "Calcined Mg-Al hydrotalcites as solid base catalysts for methanolysis of soybean oil," <i>Journal of Molecular Catalysis A-Chemical</i> , Vol. 246, No. 1-2, 2006, pp. 24-32.	Journal	2006		x						
Xie, W. L., Peng, H., and Chen, L. G., "Transesterification of soybean oil catalyzed by potassium loaded on alumina as a solid-base catalyst," <i>Applied Catalysis A-General</i> , Vol. 300, No. 1, 2006, pp. 67-74.	Journal	2006		x						
Xin, J. Y.; Imahara, H.; Saka, S. Oxidation stability of biodiesel fuel as prepared by supercritical methanol. Fuel 2008, 87 (10-11), 1807-1813.	Journal	2008		x						
Xu, H.; Miao, X.; Wu, Q. High quality biodiesel production from a microalga Chlorella protothecoides by heterotrophic growth in fermenters. Journal of biotechnology 2006, 126, 499-507.	Journal	2006			x					

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Xu, L. L.; Yang, X.; Yu, X. D.; Guo, Y. H.; Maynurkader Preparation of mesoporous polyoxometalate-tantalum pentoxide composite catalyst for efficient esterification of fatty acid. Catalysis Communications Vol.9, 2008. pp.1607-1611	Journal	2008		x						
Yamaberi, K.; Takagi, M.; Yoshida, T. Nitrogen depletion for intracellular triglyceride accumulation to enhance liquefaction yield of marine microalgal cells into a fuel oil. Journal of Marine Biotechnology 1997, 6, 44-48.	Journal	1997		x						
Yamada, H.; Sorimachi, Y.; Tagawa, T. Operation optimization of lipase- catalyzed biodiesel production. Journal of Chemical Engineering of Japan 2007, 40, 571-574.	Journal	2007		x						
Yamanaka, S.; Kouzu, M.; Kdota, K.; Shimosaka, A.; Shirakawa, Y.; Hidaka, J. Catalysis by CaO/SiO2 composite particle for biodiesel production. Journal of Thermal Analysis and Calorimetry 2007, 90945 (949).	Journal	2007		x						
Yamane, K.; Kato, T.; Okutani, H.; Shimamoto, Y. Effect of Refining Process in Biodiesel Fuel Prodcution on Fuel Properties, Diesel Engine Performance and Emissions. SAE International 2003, 2003-01-1930.	Paper	2003		x	x		x			
Yan, S. L., Lu, H. F., and Liang, B., "Supported CaO catalysts used in the transesterification of rapeseed oil for the purpose of biodiesel production," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 646-651.	Journal	2008		×						
Yang, Z. Q. and Xie, W. L., "Soybean oil transesterification over zinc oxide modified with alkali earth metals," <i>Fuel Processing Technology</i> , Vol. 88, No. 6, 2007, pp. 631-638.	Journal	2007		x						
Ye, X. J., Fernando, S., Wilson, W., and Singh, A., "Application of amphiphilic catalysts, ultrasonication, and nanoemulsions for biodiesel production process," <i>Chemical Engineering & Technology</i> , Vol. 30, 2007, pp. 1481-1487.	Journal	2007		x						
Yin, J. Z.; Xiao, M.; Song, J. B. Biodiesel from soybean oil in supercritical methanol with co-solvent. Energy Conversion and Management 2008, 49 (5), 908-912.	Journal	2008		x						
Yoon, S. H., Park, S. H., and Lee, C. S., "Experimental investigation on the fuel properties of biodiesel and its blends at various temperatures," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 652-656.	Journal	2008					x			
Yori, J. C., D'Amato, M. A., Grau, J. M., Pieck, C. L., and Vera, C. R., "Depression of the cloud point of biodiesel by reaction over solid acids," <i>Energy</i> & <i>Fuels</i> , Vol. 20, No. 6, 2006, pp. 2721-2726.	Journal	2006			x		х			
Yori, J. C., D'Ippolito, S. A., Pieck, C. L., and Vera, C. R., "Deglycerolization of biodiesel streams by adsorption over silica beds," <i>Energy & Fuels</i> , Vol. 21, No. 1, 2007, pp. 347-353.	Journal	2007		x						
Yoshimoto, Y. Performance of DI Diesel Engines Fueled by Water Emulsions with Equal Proportions of Gas Oil-Rapeseed Oil Blends and the Characteristics of the Combustion of Single Droplets SAE International 2006, 2006-01-3364.	Paper	2006				х	x			
Yoshimoto, Y.; Onodera, M. Performance of a Diesel Engine Fueled By Rapeseed Oil Blended With Oxygenated Organic Compounds. SAE International 2002, 2002-01-2854.	Paper	2002				x	x			

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Yoshimoto, Y.; Onodera, M.; Tamaki, H. Reduction of NOx, Smoke, and BSFC in a Diesel Engine Fueled by Blodiesel Emulsion with Used Frying Oil. SAE International 1999, 1999-01-3598.	Paper	1999				х	х			
Yoshimoto, Y.; Tamaki, H. Reduction of NOx and Smoke Emissions in a Diesel Engine Fueled by Biodiesel Emulsion Combined with EGR. SAE International 2001, 2001-01-0649.	Paper	2001				x	х			
Yost, D. M.; Appleby, D.; Spooner-Wyman, J. Evaluation of Di-Butoxy Glycerol (Dbg) for use as a Diesel Fuel Blend Component. SAE International 2003, 2003-01-2281.	Paper	2003			x	x	x			
You, Y. D., Shie, J. L., Chang, C. Y., Huang, S. H., Pai, C. Y., Yu, Y. H., and Chang, C. F. H., "Economic cost analysis of biodiesel production: Case in soybean oil," <i>Energy & Fuels</i> , Vol. 22, 2008, pp. 182-189.	Journal	2008							x	
Yuan, W., Hansen, A. C., and Zhang, Q., "Computational modelling of NOx emissions from biodiesel combustion," <i>International J. of Vehicle Design</i> , Vol. 45, No. 1-2, 2007, pp. 12-32.	Journal	2007				x	x			
Yuan, W., Hansen, A. C., and Zhang, Q., "Vapor pressure and normal boiling point predictions for pure methyl esters and biodiesel fuels," <i>Fuel</i> , Vol. 84, No. 7-8, 2005, pp. 943-950.	Journal	2005			x		x			
Yuan, X.; Liu, J.; Zeng, G.; Shi, J.; Tong, J.; Huang, G. H. Optimization of conversion of waste rapeseed oil with high FFA to biodiesel using response surface methodology. Renewable Energy 2008, 33 (7), 1678-1684.	Journal	2008		x						
Yuste, A. J. and Dorado, M. P., "A neural network approach to simulate biodiesel production from waste olive oil," <i>Energy & Fuels</i> , Vol. 20, No. 1, 2006, pp. 399-402.	Journal	2006		х						
Zabaniotou, A.; Ioannidou, O.; Skoulou, V. Rapeseed residues utilization for energy and 2nd generation biofuels. Fuel 2008, 87 (8-9), 1492-1502.	Journal	2008		x						
Zannis, T. C.; Rakopoulos, C. D.; Hountalas, D. T. Theoretical Study Concerning the Effect of Oxygenated Fuels on Di Diesel Engine Performance and Emissions. SAE International 2004, 2004-01-1838.	Paper	2004				x				
Zervas, E. Regulated and non-regulated pollutants emitted from two aliphatic and a commercial diesel fuel. Fuel 2008, 87 (7), 1141-1147.	Journal	2008				х				
Zhang, L. X., Guo, W. J., Liu, D., Yao, H. F., Ji, L., Xu, N. P., and Min, E. Z., "Low boiling point organic amine-catalyzed transesterification for biodiesel production," <i>Energy & Fuels</i> , Vol. 22, No. 2, 2008, pp. 1353-1357.	Journal	2008		х						
Zhang, X.; Wang, H.; Li, L.; Wu, Z.; Hu, Z.; Zhao, H.; Yang, W. Characteristics of Particulates and Exhaust Gases Emissions of DI Diesel Engine Employing Common Rail Fuel System Fueled with Bio-diesel Blends. SAE International 2008, 2008-01-1834.	Paper	2008				х				
Zhang, Y. and Boehman, A. L., "Impact of biodiesel on NOx emissions in a common rail direct injection diesel engine," <i>Energy & Fuels</i> , Vol. 21, No. 4, 2007, pp. 2003-2012.	Journal	2007				x				
Zhang, Y.; Dube, M. A.; McLean, D. D.; Kates, M. Biodiesel production from waste cooking oil: 1. Process design and technological assessment. <i>Bioresources Technol.</i> 2003, 89, 1-16.	Journal	2003		x						

Reference	Pub Type	Year	Biofuel Feed- Stock	Fuel Prod. Tech.	Fuel Props. and Specs	Vehicle Emissions	Fuel handling and Perform.	Life-Cycle Analysis	Econ.	Policy
Zheng, M., Mulenga, M. C., Reader, G. T., Wang, M. P., Ting, D. S. K., and Tjong, J., "Biodiesel engine performance and emissions in low temperature combustion," <i>Fuel</i> , Vol. 87, No. 6, 2008, pp. 714-722.	Journal	2008				x	x			
Zheng, M.; Skelton, R. L.; Mackley, M. R. Biodiesel reaction screening using oscillatory flow meso reactors. Process Safety and Environmental Protection 2007, 85, 365-371.	Paper	2008				x	х			
Zhou, C. H. C.; Beltramini, J. N.; Fan, Y. X.; Lu, G. Q. M. Chemoselective catalytic conversion of glycerol as a biorenewable source to valuable commodity chemicals. Chemical Society Reviews 2008, 37 (3), 527-549.	Journal	2008		х						
Zhou, H., Lu, H. F., and Liang, B., "Solubility of multicomponent systems in the biodiesel production by transesterification of Jatropha curcas L. oil with methanol," <i>Journal of Chemical and Engineering Data</i> , Vol. 51, No. 3, 2006, pp. 1130-1135.	Journal	2006		x						
Zhu, L. Y.; Zong, M. H.; Wu, H. Efficient lipid production with Trichosporon fermentans and its use for biodiesel preparation. Bioresource Technology 2008, 99 (16), 7881-7885.	Journal	2008			x					
Zygarlicke, C. J.; Schmidt, D. D.; Olson, E. S.; Leroux, K. M.; Wocken, C. A.; Auick, T. A.; Williams, K. D. EERC Center for Blomass Utilization 2005; U.S. DOE. DOE/GO/13055-1; Jul 28, 2008.	Report	2005			x					

Appendix III. Algae Players

Company	Location	Focus	Туре	Facility	Other Notes	Website
A2BE Carbon Capture	Boulder, CO	Deploy algae growth technology on a global industrial scale	Closed photo- bioreactor "algae water beds" for growing green micro algae	Commissioning a prototype facility in 2008 Algae oils will be processed via transesterification	Patent pending on their algae growth system	www.algaeatwork.com
AG Energy (also known as Infinifuel)	Dayton, NV	Researching growing systems using geothermal heat	Geothermally heated growing ponds	300 acre facility in Wabuska, NV	No active production reported	www.agenergycorp.com
Algae Link	Netherlands	Algae production equipment	Photo-bioreactors and green houses	Small scale (2-4 kg) pilot plant for sale	Working with Air France KLMSA to develop algae oil to be used as a jet fuel	www.algaelink.com
Algal Biomass Association		Non-profit organization dedicated to the advancement of algal biomass production technologies				www.algalbiomass.org/
Algenol Biofuels		Direct production of ethanol from algae			First commercial project expected in 2009 in Mexico	www.algenolbiofuels.com
Aquaflow Bionomic	New Zealand	Developing methods of harvesting algae and producing biodiesel	Open oxidation ponds of standard effluent management systems	Demo plant at Marlborough Sewage plant: 60 ha of open ponds		www.aquaflowgroup.com
Aquatic Energy	Lake Charles, LA	Development, construction and operation of algal growth ponds using their own process	Process system using open ponds	2 acre pilot plant 250 ha commercial plant in planning stages		www.aquaticenergy.com
Aurora BioFuels Inc	Alameda, CA	Researching methods to produce biodiesel from algal oil	Process system using open ponds			www.aurorabiofuels.com
BioCentric Energy Holdings, Inc.	Huntington Beach, CA	Flue gas from coal fired power plant for algae growth.		agreement for facility in Wuhan, China		www.biocentricenergy.com
Bioco	Canada	Harvesting technology/ Algae oils to jet fuel				www.biorefinery-technology.com/
Bionavitas	Washington State	Developing technology for high volume production growth of microalgae	Photo-bioreactors		Startup facility with plans commercialize within 4 years	www.bionavitas.com
BioProcessH20	Rhode Island	Developing photobioreactors	photobioreactors			bioprocessh2o.com
Bodega Algae	Jamaica Plain, MA	Improved methods of introducing light and nutrients to promote algae growth	Experimental photobioreactors			www.bodegaalgae.com

Company	Location	Focus	Туре	Facility	Other Notes	Website
Carlsbad Center of Excellence	New Mexico	Developing biodiesel from algae oil using test ponds	open ponds	Atoka	with General Atomics	www.ga.com
Cellana	Hawaii	Building a algae growth and oil extraction facility to produce biodiesel	Open-air ponds	Kona Demonstration Facility is 25 ha Plans to scale facility to 1000 ha in 2 years and 20,000 ha if successful	Started with Shell and HR Petroleum	www.cellana.com
Chevron	San Ramon, CA	Funding research to develop algae strains and to research bio-oil reforming			Partnership with NREL, focusing on transportation fuels	www.chevron.com
Circle Biodiesel and Ethanol Corporation	San Marcos, CA	Sells and installs biodiesel plants and biodiesel processers	Commercial photo- bioreactor and harvesting systems available for algae production	None	\$195k system processes 1 gallon of algal oil per minute	None
Community Fuels	Encinitas, CA	One R&D topic is to address key issues in commercial scale production of biodiesel from algae				www.communityfuels.com
DARPA		Funding algae research to develop military jet fuel				www.darpa.mil
Diversified Energy	Gilbert, AZ	Development and commercialization of algae growth systems (DEC-XLR Simgae™)	Photo-bioreactors (Algae Biotape™)	Currently conducting concept demonstrations at their labs and at a dairy farm in Casa Grande, AZ	Project with XL Renewables Biorefinery. \$25k-35k per acre, 40-60 tons dry algae per acre w/ oil content 10- 40%	www.diversified-energy.com
Energy Farms						
Enhanced Biofuels & Technologies	London and India	Using algae growth to reduce CO2 emissions from flue gases	Combination of photo-bioreactors and open raceway ponds	None noted		www.ebtplc.com
General Atomics	Carlsbad, NM	Develop improved processes for growing algae and extracting oil	Outdoor ponds for salt-water microalgae	Research scale plant in NM	Partnership with Center for Excellence of Hazardous Materials Management (CEHMM) and Texas Agrilife	www.ga.com
General Electric					Participating in DARPA-funded project	
Genifuel	Baltimore, MD	Gasification of algal biomass	Micro algae (including cvanobacteria)			genifuel.com

Company	Location	Focus	Туре	Facility	Other Notes	Website
Global Green Solutions	Vancouver, BC	Developing a high density vertical bioreactor (HDVB) to produce algae with supercritical oil extraction	Photo-bioreactors	Proof of concept (using chlorella algae)	Joint project with Valcent	www.globalgreensoluctionsinc.com
Green Fuel	Cambridge, MA	Developing and selling systems to recycle CO2 from smokestack, fermentation, and geothermal gases via algae growth	Not stated	"Has successfully installed systems at gas, coal, and oil burning facilities" Facility at Redhawk Power Plant in AZ w/ APS	Working with IGV to deploy bioreactor technology	www.greenfuelonline.com
Green Shift		No mention of algae on webpagejust ethanol and biodiesel from corn				www.greenshift.com
Green Star Products	Chula Vista, CA	Research on algae growth formula Montana Micronutrient Booster (MMB) Focused more on algae farming		Working to develop a high production facility	Moving to a new lab facility in Utah	www.greenstarusa.com
Honeywell UOP		Developing processing technology to convert algal oils to transportation fuels			Participating in DARPA-funded project	www.uop.com
HR BioPetroleum	San Diego, CA	Pairing algae production with industrial processes to reduce CO2 emissions	Coupled close- cultured bioreactors and open ponds in two-stage process	Kona Demonstration Facility2ha validation facility in Hawaii (with Shell and Cellana)	Looking toward commercial- scale algae growth and marketing final product	www.hrbp.com
IGV	Germany	Have commercially available photobioreactors	Photobioreactors	Existing facilities used to produce algae for cosmetics	Working with GreenFuel to deploy bioreactor technology to accelerate commercialization of biofuels from algae	www.igv-gmbh.de
Imperium Renewables	Seattle, WA	Agreement with solazyme to provide algal oil for their biodiesel facility in Seattle		Biodiesel facility in Seattle	Doesn't make or research algae	www.imperiumrenewables.com
Inventure Chemical	Seattle, WA	Algae-specific biofuel conversion processes (patent pending process)	A variety of algae species can be used, ranging from 1-10 micron and fresh- or salt-water	A commercial prototype algae biofuel processing facility in Seattle is producing biodiesel and ethanol from algae sourced from facilities in Israel, Arizona, and Australia		www.inventurechem.com

Company	Location	Focus	Туре	Facility	Other Notes	Website
Kent SeaTech Corp	San Diego, CA	Fish hatchery and aquaculture company			No mention of algae on website, however, working on algae REDUCTION for Salton Sea	www.kentseatech.com
Kwikpower	UK	Licensed algae production technology developed at NREL (Advanced Biofuels Technology)	A novel strain of microalgae developed by Dr Arthur Nonomura at UC Berkeley		No website found, article at:	http://www.greencarcongress.com/2 006/06/kwikpower_acqui.html
LiveFuels Inc	Menlo Park, CA	A national alliance of labs and scientists working on algae to biofuels			Partnership with Sandia, NREL and DOE among other private labs	www.livefuels.com
Menova Energy	Canada	Solar energy solution company	Developed a photobioreactor	Proposed pilot project	Partnering with Trident Exploration to produce algae from processing of petroleum products	www.power-spar.com
MidContinental		Biodiesel facility, no mention of				www.mcchemical.com
Midwest Research Institute	Kansas City	New center for algal research	No dedicated employees		No dedicated staff, but an aknowledgment of function of algal research	http://www.mriresearch.org/
National Algae Association	The Woodlands, TX	National trade association for the algae industry				www.nationalalgaeassociation.com
National Renewable Energy Lab (NREL)	Golden, CO	Federally funded research organization investigating algae-to-fuels technologies				www.nrel.gov
Neptune Industry	Florida	Fish farm and aquaculture	"Floating sock" in a rock quarry fed with fish waste	Projected yields of 10,000 gallons/acre	Florida farm to Fuel grant	
Old Dominion University	Virginia	Algae growth for wastewater treatment	algae at municipal sewage treatment plants		No specific website, article found at:	http://www.odu.edu/oduhome/ news/spotlight111.shtml
Oregon State Univ Sustainable Technologies Lab	Corvallis, OR		Experimental photobioreactors			
Organic Fuels	Houston, TX	Sponsored research on extraction of oil from algae (University of Texas, Austin)				www.organicfuels.com

Company	Location	Focus	Туре	Facility		Other Notes	Website
Originoil	Los Angeles, CA	Algae cultivation and oil extraction (patent pending technology)	Photo-bioreactor with Quantum Fracturing™ (water, CO2 and other nutrients are fractured at high pressure and injected into system) Extraction via proprietary catalysts	None mentioned			<u>www.originoil.com</u>
PetroAlgae	Melbourne, FL	Commercializing technologies to grow and harvest oil from algae	Natural strains of micro-algae developed by University of Arizona Cultivated in photo- bioreactors	R&D site at Fellsmere, FL	Plan o	on 1 year to commercial	www.petroalgae.com
PetroSun BioFuels Refining	Arizona	Operations include oil and gas exploration, development, production, oilfield tubular sales and algae-to-algal oil alternative biofuel production	Open growing ponds	1100 acres of growing ponds at developing facility in Rio Hondo, TX	Appro plant waste in AZ comm Queen Icon I negot New S	oved plans for a pilot to produce algae at a e water treatment plant . Planning on building a hercial farm system in hsland, Australia with Energy. Also engaged in iations to build facility in South Wales, Australia.	www.petrosuninc.com
Primafuel	California	Commercializing algae technologies	ponds		Algae	Biorefinery Program	www.primafuel.com
San Diego Center for Algae-Based Biofuels	California	Research to make algae-based biofuel production a reality			R&D (consortium	<u>None</u>
Sapphire Energy	San Diego	Developing a platform that produces "green crude" and biohydrocarbon fuels from a modified algae	Photobioreactors		Renev gasoli worki Renev	wable 91 octane ine, not biodiesel. Also ng with Imperium wables on jet fuel.	www.sapphireenergy.com/
Seambiotic	Israel	Utilizing flue gas from coal fired power plants to simulate algae growth.	Open Ponds	Facility near Israel Electric Corp. on the Mediterranean near Ashkelon, Israel.			www.seambiotic.com
Shell							http://www.shell.com/home/content/r esponsible_energy/energy_for_the_ future/biofuels/biofuels_22032008.ht ml

Company	Location	Focus	Туре	Facility	Other Notes	Website
Solazyme	South San Francisco, CA	Conducts research to synthetically evolve marine microbes to produce a variety of valuable products using proprietary genetic engineering method	Microbial fermentation process that allows algae to produce oil quickly and efficiently, without sunlight Process can utilize waste glycerol and many cellulosic materials		SoladieselRD™ passed ASTM D-975 specifications.	www.solazyme.com
Solix Biofuels	Fort Collins, CO	Designing and building photobioreactors that can produce algae on a large scale Researching different types of algae	Photobioreactors	Planning on building test reactor that will utilize CO2 from New Belgium Brewing Co	http://www.popsci.com/node/1016 4	www.solixbiofuels.com
SSC GmbH	Germany	Sequestering CO2 from power plants using algae and converting it to biofuels.	Bio-photo-reactor	Pilot plant at E.On Hanse AG in Hamburg-Reitbrook		
StarEnergy Co.	USA	Integrating algae growth and oil recovery.		Plans for 100 million gallon/ year oil refinery.		http://www.starenergyco.com/
Sunrise Ridge Algae Inc.	Houston, TX	Research activities in: algae species, reducing the capital and costs of algae greenhouses and concentration and separation, and optimizing growth and harvesting protocols,	research, development and commercialization of algae biomass technology for reduction of water and greenhouse gas pollutants and production of renewable fuel feed stocks and animal feeds	owns and operates a pilot production facility at the Austin Water Utility's Hornsby Bend plant in Austin, Texas.		<u>www.sunrise-ridge.com</u>
Tamil Nadu Agricultural University and Bharat Petroleum Corp.	India	Develop pilot plant technology for biodiesel production from algae		MoU to develop a pilot plant	Project would be for three years, depending on nature of success.	http://www.tnau.ac.in/aabout.html
Targeted Growth		No mention of algae on webpage				www.targetedgrowth.com
Texas Agrilife Research	Texas	Phased R&D program for developing promising algae strains, algae production systems, and algae oil separation systems	Microalgae	Initial demonstration facility could be scaled to 2,000 acres	\$4M research contract with General Atomics.	www.agriliferesearch.tamu.edu

Appendix III (cont.)

Company	Location	Focus	Туре	Facility	Other Notes	Website
Texas Clean Fuels						no web page, maybe an initiative
Trident Exploration	Canada	Natural gas exploration and development company focused on Natural Gas from coal	Developed a photobioreactor	Proposed pilot project	Partnering with Menova Energy to produce algae from processing of petroleum products.	www.tridentexploration.ca
Univenture	Ohio	Developing and improving growing ponds and harvesting methods.	growing ponds			www.univenture.com
University of Minnesota, Center for Biorefining	Minnesota	Developing ways to grow mass quantities of algae, identifying promising strains, and exploring options for treating residues	Algae is grown in sewage plant discharge			/biorefining.cfans.umn.edu
University of New Hampshire Biodiesel Group	New Hampshire	Investigating redesigning waste water treatment plants to use raceway ponds to grow algae for biodiesel extraction	Open raceway ponds		Also investigating using algae mush as a fertilizer	www.unh.edu/p2/biodiesel/
University of North Dakota Energy and Environmental Research Center	Grand Forks, ND	EERC has a biomass utilization research program which includes all types of feedstocks			Research CO2 sequestration with switchgrass and algae.	www.undeerc.org/programareas/ren ewableenergy
University of Texas	Texas	Provides nearly 3000 strains of algae to the community	Researching cyanobacteria for biofuels in photobioreactors	Lab-scale		www.utex.org
US Sustainable Energy	Texas	Biodiesel producer and supplier	Testing biodiesel production from algae oil supplied by Green Star	Under negotiations to install photobioreactors from Green Star		www.ussec.us
Valcent Products	Vancouver, BC El Paso, TX	Researches and develops life- enhancing products	High-Density Vertical Photo-bioreactor (HDVP)	Research facility in El Paso, TX	Working with Global Green Solutions	www.valcent.net
Xcel Energy	Minnesota	Utility provider, funding algae research	Utility			www.xcelenergy.com
XL Renewables	Phoenix, AZ	Algae biomass production technology	Developed XL super trough liner for open algae ponds	Algae Development Center on 25 acres in Casa Grande, AZ to test production system design and operation, algae variety development, and system optimization		www.xldairygroup.com

Appendix IV. Composition and Properties of Biodiesel Fuel and its Precursors

Appendix IV -1 Fatty Acid Precursors to Biodistillates

Appendix IV-2 Compositional Profiles of Triglycerides (wt.%)

Appendix IV-3 Typical Properties of Vegetable Oils and Animal Fats

Appendix IV-4 Typical Properties of Biodiesel (FAME) and Renewable Diesel

Common Name	Formal Name	CAS. No.	Abbreviation	Molecular Formula	Molecular Weight	Molecular Structure
Caproic Acid	Hexanoic Acid	142-62-1	6:0	$C_6H_{12}O_2$	116.16	ОЦОН
Caprylic Acid	Octanoic Acid	124-07-2	8:0	$C_8H_{16}O_2$	144.22	ОН
Capric Acid	Decanoic Acid	334-48-5	10:0	$C_{10}H_{20}O_2$	172.27	ОЦОН
Lauric Acid	Dodecanoic Acid	143-07-7	12:0	$C_{12}H_{24}O_2$	200.32	ОН
Tridecylic Acid	Tridecanoic Acid	638-53-9	13:0	$C_{13}H_{26}O_2$	214.35	оди
Brassylic Acid	1,11-Undecane-dicarboxylic Acid	505-52-2	13:0	$C_{13}H_{24}O_4$	244.33	но о о о
Myristic Acid	Tetradecanoic Acid	544-63-8	14:0	$C_{14}H_{28}O_2$	228.38	O OH
Myristoleic Acid	cis-9-Tetradece-noic Acid	544-64-9	14:1	$C_{14}H_{26}O_2$	226.26	O OH
Pentadecanoic Acid	Pentadecanoic Acid	1002-84-2	15:0	$C_{15}H_{30}O_2$	242.40	ОН
Pentadecenoic Acid	cis-9-Pentadecenoic Acid		15:1	$C_{15}H_{28}O_2$	240.28	O OH
Palmitic Acid	Hexadecanoic Acid	57-10-3	16:0	$C_{16}H_{32}O_2$	256.43	ОН
Palmitoleic Acid	cis-9-Hexadecenoic Acid	373-49-9	16:1	C ₁₆ H ₃₀ O ₂	254.42	O OH

Common Name	Formal Name	CAS. No.	Abbreviation	Molecular Formula	Molecular Weight	Molecular Structure
Hexadecadienoic Acid	cis-9,12-Hexadecadienoic Acid		16:2	$C_{16}H_{28}O_2$	252.40	O UH OH
Hexadecatrienoic Acid	cis-7,10,13-Hexadecatrienoic Acid		16:3	$C_{16}H_{26}O_2$	250.38	ОН
Margaric Acid	Heptadecanoic Acid	506-12-7	17:0	$C_{17}H_{34}O_2$	270.46	ОН
Heptadecenoic Acid	cis-9-Heptadecenoic Acid		17:1	$C_{17}H_{32}O_2$	268.44	ОН
Stearic Acid	Octadecanoic Acid	57-11-4	18:0	$C_{18}H_{36}O_2$	284.48	ОН
Oleic Acid	cis-9-Octadecenoic Acid	112-80-1	18:1	$C_{18}H_{34}O_2$	282.47	ОН
Ricinoleic Acid	12-Hydroxy- <i>ci</i> s-9- Octadecenoic Acid	141-22-0	18:1	$C_{18}H_{34}O_3$	298.46	OH O OH OH OH
Linoleic Acid	cis-9,12-Octadecadienoic Acid	60-33-3	18:2	$C_{18}H_{32}O_2$	280.46	ОН
Linolenic Acid	cis-9,12,15-Octadecatrienoic Acid	463-40-1	18:3	$C_{18}H_{30}O_2$	278.44	O U OH
Stearidonic Acid	cis-5,8,11,14- Octadecatetraenoic Acid	20290-75-9	18:4	$C_{18}H_{28}O_2$	276.40	O OH
Nonadecylic Acid	Nonadecanoic Acid	646-30-0	19:0	$C_{19}H_{38}O_2$	298.51	ОН
Arachidic Acid	Eicosanoic Acid	506-30-9	20:0	$C_{20}H_{40}O_2$	312.54	ОН
Gondoic Acid	cis-11-Eicosenoic Acid	5561-99-9	20:1	C ₂₀ H ₃₈ O ₂	310.53	ОН

Common Name	Formal Name	CAS. No.	Abbreviation	Molecular Formula	Molecular Weight	Molecular Structure
Auricolic Acid	cis-11,14-Eicosadienoic Acid	2091-39-6	20:2	$C_{20}H_{36}O_2$	308.51	O OH OH
Eicosatrienoic Acid	cis-8,11,14- Eicosatrienoic Acid	1783-84-2	20:3	$C_{20}H_{34}O_2$	306.49	
Arachidonic Acid	cis-5,8,11,14-Eicosatetraenoic Acid	506-32-1	20:4	$C_{20}H_{32}O_2$	304.48	O OH
Eicosapentaenoic Acid	cis-5,8,11,14,17- Eicosapentaenoic Acid	10417-94-4	20:5	$C_{20}H_{30}O_2$	302.46	
Behenic Acid	Docosanoic Acid	112-85-6	22:0	$C_{22}H_{44}O_2$	340.60	ОН
Erucic Acid	cis-13-Docosenoic Acid	112-86-7	22:1	$C_{22}H_{42}O_2$	338.58	O OH OH
Docosadienoic Acid	cis-13,16-Docosadienoic Acid	17735-98-7	22:2	$C_{22}H_{40}O_2$	336.56	O OH OH
Docosatrienoic Acid	cis-13,16,19-Docosatrienoic Acid	28845-86-5	22:3	$C_{22}H_{38}O_2$	334.54	O U OH
Adrenic Acid	cis-7,10,13,16- Docosatetraenoic Acid	122068-08-0	22:4	$C_{22}H_{36}O_2$	332.52	O UH
Docosapentaenoic Acid	cis-7,10,13,16,19- Docosapentaenoic Acid	2006-01-1	22:5	$C_{22}H_{34}O_2$	330.50	о Ш он
Docosahexaenoic Acid	cis-4,7,10,13,16,19- Docosahexaenoic Acid	6217-54-5	22:6	$C_{22}H_{32}O_2$	328.49	
Lignoceric Acid	Tetracosanoic Acid	557-59-5	24:0	$C_{24}H_{48}O_2$	368.65	ОН
Nervonic Acid	cis-15-Tetracosenoic Acid	506-37-6	24:1	$C_{24}H_{46}O_2$	366.63	OH OH

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Fatty Acid	ł	Almond			Bay			Castor		Сосоа			Cotton-seed
Common Name	Abbrev.	Kernel	Andiroba	Babassu	Laurel leaf	Camelina	Canola	Oil	Caycuma	Butter	Coconut Oil	Corn Oil	Oil
Capriotic	6:0										.45		
Caprylic	8:0			2.6 - 7.3							.7 - 9.8		
Capric	10:0			1.2 - 7.6							.6 - 9.7	3.9	
Lauric	12:0			40 - 48							44.6 - 54.1		
Tridecylic	13:0												
Myristic	14:0			11 - 27							13 - 20.6	.1 - 2	0 - 2
Myristoleic	14:1												
Pentadanoic	15:0												
Pentadecenoic	15:1												
Palmitic	16:0	6.5	27	5.2 - 11	25.9	5.4	1.5 - 6	.7 - 1.1		26	6.1 - 10.5	7 - 13	11.7- 28
Palmitoleic	16:1	1.4	1		0.3						0.1	.2 - 1.6	
Hexadecadienoic	16:2												
Hexadecatrienoic	16:3												
Heptadecanoic	17:0											.1	
Heptadecenoic	17:1												
Stearic	18:0	70.7	7	1.8 - 7.4	3.1	2.6	1 - 2.5	.9 - 3.1	2.5	34	1 - 3.8	1 - 5	.9 - 5
Oleic	18:1	20	49	9 - 20	10.8	14.3	52 - 66	2.8 - 4.9	50.2	35	5 - 8.8	19 - 49	13 - 35
Ricinoleic	18:1							90.2					
Linoleic	18:2		16	1.4 - 6.6	11.3	14.3	16.1 - 31	1.3 - 4.4	40.6	3	.4 - 2.7	39 - 62.5	40 - 58
Linolenic	18:3				17.6	38.4	6.4 - 14.1	0.2	6.7		.13	0 - 3	trace
Stearidonic	18:4												
Arachidic	20:0					0.3		0.2			0.1	.46	
Gondoic	20:1					16.8		0.4					
Auricolic	20:2												
Eicosatrienoic	20:3												
Arachidonic	20:4												
Eicosapentaenoic	20:5												
Behenic	22:0					1.4							
Erucic	22:1					2.9	1 - 2						
Adrenic	22:4												
Clupanodonic	22:5												
Docosahexaenoic	22:6												
Lignoceric	24:0												
Nervonic	24:1												
References		(93)	(65)	(345)	(93)	(77)	(345)	(346,347)	(250)	(199)	(348,349,350,146, 351,184,345)	(348,272,107,345, 352,94,184)	(351,353,94,107,3 45)

Appendix IV-2 (cont.))
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Fatty Acid		Crambo	Cumoru	Cuphoa	Cunoro	Enoxy Oilo	Ethiopian	Hazelnut	latropha	Karania		Lincod	Mahua
Common Name	Abbrev.	Crambe	Culliaru	Cupilea	Cyllara	Epoxy Olis	Mustard	Kernel	Jatropha	Naralija	Lesquerena	Linseed	Mariua
Capriotic	6:0												
Caprylic	8:0			.2 - 73									
				5.3 -									
Capric	10:0			95.3									
Lauric	12:0			.2 - 81.4					0.3				
Tridecylic	13:0			0 07 0									
Myristic	14:0			.2 - 67.9	.1				.1				
Myristoleic	14:1					-				-			
Pentadanoic	15:0					-				-			
Pentadecenoic	15:1					0.0.4.4		1.0	10 17	07.447			
Palmitic	16:0	2	23		11 - 14	2.8 - 4.1	5.3 - 5.4	4.9	12 - 17	3.7 - 11.7	1 - 5.8	4 - 7	16.0 - 37
Palmitoleic	16:1				0.1	-		0.2	.4 - 1.4	-	.5 - 1.4	0.3	
Hexadecadienoic	16:2					-				-			
Hexadecatrienoic	16:3					-				-			
Heptadecanoic	17:0												
Heptadecenoic	17:1		_										
Stearic	18:0	1	7		3 - 3.7	1.1 - 2.6	0.2	2.6	5.4 - 9.7	2.4 - 8.9	1.5 - 5.4	2 - 5	18.6 - 25.1
Oleic	18:1	19	37		25	4.0 - 20.7	10 - 43.2	83.6	37 - 63	44.5 - 71.3	11.8 - 27	21 - 40	32 - 51
Ricinoleic	18:1												
Linoleic	18:2	9	29		56 - 59.9	9.2 - 13.7	24.6 - 36	8.5	19 - 41	10.8 - 18.3	3 - 7.6	5 - 40	8.9 - 18
Linolenic	18:3	7				.1 4	15.2 - 16.5	0.2	0.8	2.7	.9 - 13.1	25 - 60	0 - 1
Stearidonic	18:4												
Arachidic	20:0	2			0.4					3.4	0.8		0 - 3.3
Gondoic	20:1				0.2						56.3		
Auricolic	20:2										3.5		
Eicosatrienoic	20:3												
Arachidonic	20:4												
Eicosapentaenoic	20:5												
Behenic	22:0	1											
Erucic	22:1	59					43.6						
Adrenic	22:4												
Clupanodonic	22:5												
Docosahexaenoic	22:6												
Lignoceric	24:0	1								1.1 - 3.5			
Nervonic	24:1												
References		(94)	(65)	(354)	(71,73)	(354)	(69)	(93)	(355,356,357,35 3,358,352,359)	(356,353,94,359)	(347,354)	(355,107,94, 360,345)	(357,94)

Appendix IV-2 (cont.)
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Fatty Aci	d	Microalgoo	Milkweed	Noom	Olive	Palm	Polm Oil	Boonut	Diqui	Polongo	Рорру	Rape	Dice Bron
Common Name	Abbrev.	wicroalgae	Oil	Neem	Olive	Kernel Oil	Failli Oli	reallut	Fiqui	Polaliya	Seed	Seed	RICE DI dII
Capriotic	6:0					0.2							
Caprylic	8:0					3.3 - 4.0	0.1	.1					
Capric	10:0				7.3	3 - 4.3	0.1					0.6	
Lauric	12:0	0.0 - 7.4			0 - 1.3	48.4 - 50.8	.3 - 2.4	0.7				trace	
Tridecylic	13:0						1.0						
Myristic	14:0	0.22 – 18.8		.23	7 - 20	15 - 17.4	.5 - 47.5	.4				.1 - 1.5	.46
Myristoleic	14:1	0.1 - 15											
Pentadanoic	15:0												
Pentadecenoic	15:1												
Palmitic	16:0	2.9 – 50.9	5.9	13.6 - 16.2	.5 - 11	8 - 9.1	3.5 - 48.8	6 - 13.7	40	12.0	12.6	1 - 7.3	11.7 - 16.5
Palmitoleic	16:1	0.1 – 39.3	6.8		0.346		.2 - 1.8				0.1	0.13	0.3
Hexadecadienoic	16:2	1.1 – 7.5											
Hexadecatrienoic	16:3	1.1 – 11.7											
Heptadecanoic	17:0						.1					.1	
Heptadecenoic	17:1												
Stearic	18:0	0.3 - 11.4	2.3	14.4 - 24.1	1.8 - 84.5	2.1 - 2.7	1.7 - 53	2 - 8.9	2	13	4	0 - 3.5	1.7 - 2.5
Oleic	18:1	0.2 – 38.7	34.8	49.1 - 61.9	3.5 - 84	11.9 - 15.1	6 - 52	36.4 - 65	47	34	22.3	8 - 73	39.2 - 43.7
Ricinoleic	18:1												
Linoleic	18:2	0.6 – 31.2	48.7	2.3 - 15.8	5.8 - 17.6	2.1 - 2.4	5 - 14	13 - 47.8	4	38.3	60.2	9.5 - 35.2	26.4 - 35.1
Linolenic	18:3	0.1 – 25.2	1.2		trace6	0.1	.26	.5 - 29.2		0.3	0.5	.4 - 60	1.1
Stearidonic	18:4	0.4 – 30.7											
Arachidic	20:0	0.3 - 22.6	0.2				0.3	1 - 4				.7 - 7.4	.46
Gondoic	20:1	0.3 - 0.4			0.3			1.2				1 - 12.1	0.4
Auricolic	20:2											0.6	
Eicosatrienoic	20:3												
Arachidonic	20:4	0.2 – 8.7											
Eicosapentaenoic	20:5	0.9 – 88.2											
Behenic	22:0	8.4						2 - 3				.4 - 2.1	
Erucic	22:1							.12				.4 - 60	
Adrenic	22:4												
Clupanodonic	22:5	22.7 – 34.3											
Docosahexaenoic	22:6	0.1 – 9.9											
Lignoceric	24:0	<15						1				0.2	.49
Nervonic	24:1											.2 -34.8	
References		(361,362,363,364 ,365)	(74)	(94)	(107,184,93,69, 345)	(350,146,184)	(348,349,350,351 ,65,352,93,345)	(351,107,352,94, 184,345)	(65)	(353)	(93)	(366,241,348, 349,107,352, 359,184,345)	(94)

Fatty Acid		Rubber	Safflower	Sal	Sosamo	Soapnut	Soybean	Spring	Sunflower	Sunola	Tucum	Vann	Walnut
Common Name	Abbrev.	Seed Oil	Samower	Jai	Sesame	Oil	Oil	Mustard	Oil	Sunoia	oil	Valili	Kernel
Capriotic	6:0												
Caprylic	8:0										1.9	2.5 - 3.9	
Capric	10:0										2.1	.7 - 5.1	
Lauric	12:0						trace				52.5	35.6 - 49.6	
Tridecylic	13:0												
Myristic	14:0		.1				.13		.2		25.0	26.4 - 50.8	
Myristoleic	14:1												
Pentadanoic	15:0												
Pentadecenoic	15:1												
Palmitic	16:0	10.2 - 11	4.8 - 10.6	4.5 - 8.6	7.2 - 13	4.7	2.3 - 13	2.4 - 4.2	3 - 8	3	7.5		7.2
Palmitoleic	16:1					.4	.13		0.1				0.2
Hexadecadienoic	16:2												
Hexadecatrienoic	16:3												
Heptadecanoic	17:0						11.4						
Heptadecenoic	17:1												
Stearic	18:0	8.7 - 12	1.2 - 4.8	34.2 - 44.8	4 - 7.7	1.5	2 - 27.2	1 - 3	1 - 6.5	4.4	0.5	5 - 8.3	1.9
Oleic	18:1	17 - 24.6	8.8 - 74.4	34.2 - 44.8	35 - 53	52.6	16.7 - 84	11.2 - 64.5	11.6 - 43	88.2	8.4	2.1 - 2.2	18.5
Ricinoleic	18:1												
Linoleic	18:2	35 - 39.6	19.7 - 83.8	2.7	30 - 48	4.7	1.6 - 57.1	9.2 - 30.2	44 -77.9	4.3	2.1		56
Linolenic	18:3	16.3 - 24				2	1.2 - 11	4.2 - 12.9	0 - 8.2	0.1			16.2
Stearidonic	18:4												
Arachidic	20:0	1		6.3 - 12.2		7	0.2		.3 - 4			2.2 - 4.7	
Gondoic	20:1					23.9	.332	2.6 - 16.6	0.3				
Auricolic	20:2												
Eicosatrienoic	20:3												
Arachidonic	20:4												
Eicosapentaenoic	20:5												
Behenic	22:0					1.5	.14		.8 - 1				
Erucic	22:1					1.1	03	1.1 - 50.7					
Adrenic	22:4												
Clupanodonic	22:5												
Docosahexaenoic	22:6												
Lignoceric	24:0					.5			0.3				
Nervonic	24:1						trace						
References		(62,353)	(148,351,107, 94,127)	(94)	(94,345)	(352)	(366,241,348, 349,367,107, 37,184,345)	(273)	(272,366,73,35 2,359,127)	(351)	(63)	(357)	(93)

Fatty Acid			Yellow	Animal Fats									
Common Name	Abbrev.	Wheat Grain	Grease	Butter	Hog Lard	Beef Tallow	Fish Oil *	Chicken and Turkey	Sheep				
Capriotic	6:0												
Caprylic	8:0			5.5									
Capric	10:0			3	0.1								
Lauric	12:0		trace	3.6	0.1	.11	0.4	0.1					
Tridecylic	13:0						.2						
Myristic	14:0		trace - 2.4	7 - 11.6	1 - 2	2.1 - 8	10.3	.8 - 1	3				
Myristoleic	14:1					.9	.2	.2					
Pentadanoic	15:0				.1	.5	1	.1					
Pentadecenoic	15:1						.1						
Palmitic	16:0	20.6	11.9 - 23.2	24 - 33.4	24 - 30	23.3 - 37	20.8	20 - 25.3	21				
Palmitoleic	16:1	1	trace - 4.6		2 - 3.3	.1 - 5	12.7	6 - 7.2	2				
Hexadecadienoic	16:2						1.9						
Hexadecatrienoic	16:3						2.3						
Heptadecanoic	17:0				.4	1-1.5	.8	.1					
Heptadecenoic	17:1				.2	.8	.3	.1					
Stearic	18:0	1.1	1.6 - 13.4	10 - 13	12 - 18	9.5 - 34.2	3.3	6 - 6.5	25				
Oleic	18:1	16.6	31.3 - 80.3	28 - 31	40 - 50	14 - 50	9.8	37.7 - 40	34				
Ricinoleic	18:1												
Linoleic	18:2	56	.6 - 50.8	1 - 3.1	7 - 13	1.5 - 50	1.6	17 - 24	5				
Linolenic	18:3	2.9	0 - 1.3	.25	0 - 1	07	1.9	.8 - 2	3				
Stearidonic	18:4						2.5						
Arachidic	20:0		.1 - 1.1		.25	.2 - 1.2	0.2	0.2					
Gondoic	20:1		.2 - 1.3		0.7	.351	1.3	0.3					
Auricolic	20:2				0.1		0.4						
Eicosatrienoic	20:3						0.4						
Arachidonic	20:4						2.3						
Eicosapentaenoic	20:5						12.5						
Behenic	22:0		.38		0.2	.11	0.2						
Erucic	22:1		trace		0.1	.11	0.3						
Adrenic	22:4						0.3						
Clupanodonic	22:5						2.5						
Docosahexaenoic	22:6						7.1						
Lignoceric	24:0						0.1						
Nervonic	24:1		02		trace	trace	0.3						
References		(93)	(154,107,69,108)	(351,107)	(199,107)	(199,107,352,93,127,345)	(348)	(199)	(199)				

* Fish Oil contains some odd fatty acids not listed

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Name	Sulfur Content, ppm	Viscosity @ 40° C, mm ² /s	Cloud Point, °C	Flash Point, °C	Pour Point, °C	Cetane No.	Lower Heating Value, MJ/kg	Specific Gravity	References
Vegetable Oils								•	
Ailanthus		30.2		240			37.04ª		(273)
Babassu		30.3	20	150		38.0			(43)
Bay Laurel		23.2		226			36.95ª		(273)
Beech		34.6		242			37.22ª		(273)
Beechnut		38.0		260			37.42 ^ª		(273)
Canola		30.2	-2 - 13	270 - 290	-9	49.4	37.62	0.88	(36,213,108)
Castor		239 297		260 - 310	-32		39.50 ^ª		(346,250,345)
Caycuma					63		39.68		(250)
Coconut		27.0		231			36.13ª		(146)
Corn		34.9 - 35.4	-1	259 - 277	-40	37.6	37.13 – 37.28	0.91	(43)
Cottonseed	8 - 10	33.5 - 50.0	2	110 - 251	-155	42 - 57	38.80 - 40.36	.8691	(368,239,43,369,370,150)
Crambe		53.6	10	274 - 284	-12	44.6	39.83 - 40.50		(43)
Ethiopian Mustard		33.8 - 118.8		212 - 245			37.20 ^a		(68,250,273)
Ground Nut			23				36.01		(71)
Hazelnut		24.0 - 31.0		180 - 230	-15	52.6	36.97 – 39.75 ^ª		(273,223,371)
Jatropha	21.5	18.2 - 49.9		174 - 240		45.0	38.50 - 39.78	0.92	(273,59,372)
Karanja	7.1	27.8 - 69.9	0	205 - 232	-3 - 6	37.5 - 39	34.00 - 42.49	0.91	(150,373,372)
Linseed	8 - 10	22.1 - 39.8	2	108 - 241	-154	34.6	39.30 - 39.75	.865903	(122,43,68,273,357,374)
Mahua	8.2	24.6 - 37.2		238 - 260	12 - 15	43.5 - 53	36.00 - 40.00	0.90	(375,76,94,374)
Neem		33.9				51.0	39.60		(375,376)
Olive		29.8		231			37.13ª		(273,371)
Palm Oil		24.1 - 39.6	31	228-267		42.0	37.36 ^ª		(43,273)
Palm Kernel		31.1		264			36.28 ^ª		(146)
Peanut		39.6	13	271	-7	41.8	37.42 ^ª		(43)
Polanga		72.0		221			39.25	0.90	(273,377,297)
Poppy Seed		42.4		265			36.57 – 37.35 ^ª		(273,377)
Rape Seed		37.0- 37.3	-4	246 - 258	-32	37.6	37.60 - 39.52	0.88	(76,378,43,36)
Rape Seed			8	191			36.38 ^ª		(71)
Rice Bran		44.5					39.50	0.92	(94)
Rubber Seed		66.2	14	198	-1		37.50	0.91	(62,54)
Safflower		31.3 - 41.2	18	260 - 275	-7	41.3	37.13 – 37.40 ^a		(43)
Sesame		35.5	-4	260	-9	40.2	36.95 ^ª		(43)
Soybean	0	28.0 - 32.6	-4 - 12	141 - 254	-12 - 0	37.6 - 57.6	37.42 - 39.60	0.88	(36,379,43,213,380,62,260,381,284,107)
Spruce		35.6		240			37.20 ^a		(273)

Name	Sulfur Content, ppm	Viscosity @ 40° C, mm²/s	Cloud Point, °C	Flash Point, °C	Pour Point, °C	Cetane No.	Lower Heating Value, MJ/kg	Specific Gravity	References
Vegetable Oils									
Sunflower		33.9	7	274	-158	37.1	39.60		(43)
Sunflower			-1	187	-8	49.4	36.57 ^ª		(71)
Tobacco Seed		27.7 - 101							(76)
Used Cooking Oil		35.3	3 - 14	147 - 177	11	63.2			(213,381,382)
Vann	18	44.6		254	36				(357,273)
Walnut		36.8		251					(273)
Yellow Grease	2 - 40		-7 - 13	83 - 284	-4	45 - 64	37.20 – 39.55		(178,154,213,378,223,383,43)
Animal Fats/Oils					•				
Beef Tallow		51.2		201			40.06		(345)
Poultry Fat			4 - 15	113 - 134					(213)
Algae Oils									
							36.00		(384)

Footnotes:

a Higher heating values were reported in the literature. Values shown here were reduced by 6% to estimate lower heating values

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Feedstock	Sulfur Content, ppm	Viscosity @ 40° C, mm ² /s	Cloud Point, °C	Pour Point, °C	Flash Point, °C	Cetane No.	Lower Heating Value, MJ/kg	Specific Gravity	References
					FAME				•
B Carinata		4.9	-9	-6	163	56.9	39.55		(68,346,385)
Babassu	5	3.6	4		112 - 127	63.0	31.80	0.88	(64,43)
Canola		3.9	-2	-6	146	52.9	40.00		(386,377)
Castor		13.8			120				(346,387)
Coconut		2.7		-5		57.0	35.22		(350)
Corn		3.6 - 4.5	-3	-3	111 - 154	65.0	38.48 - 41.14		(273,154,345,377)
Cottonseed		3.8		-4	110 - 182	45.5 - 51.2	41.18		(273,345,377)
Crambe		5.1			190		41.98		(273,345,377)
Cyrana		3.6	-1		175	48.6 - 59	37.20		(72,73)
Hazelnut		3.6 - 5.4			152 - 183	55.0	37.23 – 41.12	0.88	(273,388,178,377)
Jatropha	3 - 100	3 - 5.7	4	3	130 - 180	36.7 - 58.4	38.45 - 41.00	0.86	(389,375,380,355,62,175,389,375,390,37 3,55,59,122,260,391,71,392)
Karanja	3 - 30	4.2 - 5.7	-2 - 24	-6 - 14	141-170	48 - 55.1	36.72 - 37.43		(369,382,393,373,359)
Linseed	50	2.8 - 5.0	-4	-145	142 - 192	30.0	37.00 - 39.75	0.89	(148,122,355,394,150)
Mahua	164.8	4.0 - 5.0		6 - 15	120 - 208	65.4	37.00		(357,76,395,150)
Microalgae		5.2		-12	115		38.54	0.87	(396)
Mustard		4.1			169		41.30		(273,377)
Olive	1	4.2 - 4.6	-2	-3	174 - 210	51 - 61	37.29 - 41.35		(150,345,377)
Palm Oil	40	2.9 - 5.6	-47	-35	162 - 168	54.6 - 66.5	33.50 - 37.10	0.88	(397,350,296,43,76,373,359)
Peanut		4.9	5		176	54.0	33.60	0.88	(43)
Polanga		4.9	13	4	140		38.66		(353)
Pongamia	1	4.5 - 5.5	13	13 - 15	125 - 171	52.8 - 61.4	36.01 - 41.30	0.88	(356,357,273,398,54,392,53,390)
Rape Seed	1-5	4.5 - 5.0	-30 - 2	-1	111 - 153	49 - 54.7	32.10 - 39.83	0.88	(176,399,382,72,400,401,120,394)
Rice Bran		4.5 - 5.3	-4 - 9	-32	152 - 265	51.6 - 63.8	37.70 - 42.20	.8888	(398,369,61,358)
Rubber Seed		4.7 - 5.8	4	-84	130 - 174		36.50 - 38.90	.8793	(62,76)
Safflower	11	4.1 - 4.3	-52	-68	176	49.8 - 52.3	40.06 - 45.21	0.88	(148,150,345)
Vann	1200	3.3		3	130				(273,357)
Sesame		3.0			145		40.90		(150)
Soy Oil	20	4.0 - 5.1	-25 - 2	-36 - 0	114 - 288	47.4 - 59.0	37.10 - 39.72	.8889	(391,260,359)
Sunflower		4.2 - 4.6	0 - 3		164 - 183	47 - 56.4	33.50 - 37.40	86	(72,73)

Appendix IV-4 (cont.)

Feedstock	Sulfur Content, ppm	Viscosity @ 40° C, mm2/s	Cloud Point, °C	Pour Point, °C	Flash Point, °C	Cetane No.	Lower Heating Value, kJ/kg	Specific Gravity	References
Tallow		5.0	12 - 16	9 - 13	96 - 188	61.8	37.54 – 39.97		(345)
Tobacco Seed		3.5 - 5.2					44.63		(76)
Walnut		4.1			170	59.9	41.32		(377)
					Renewable Die	sel			
Hydrotreated Vegetable Oil (HVO)		2.9 - 3.5	-255			80 - 99			(297)
Green Diesel	1		-10 - 20			70 - 90	44.00	0.78	(178)
NExBTL	0	2.9 - 3.5	-530			84 - 99	44.00	0.7779	(175)

Footnotes:

a Higher heating values were reported in the literature. Values shown here were reduced by 6% to estimate lower heating values

Appendix V. Emissions Effects of Biodistillates

Appendix V -1 Exhaust Emissions from Biodistillates

Appendix IV-2 Aldehyde Emissions from Biodistillates

Appendix V-1. Exhaust Emissions from Biodistillates

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Agarwal, A. K. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion Engines. Progress in Energy		B100 Sunflower Oil			Steady State		200 - 2100 (ppm)		150 - 350 (ppm)	0.025 - 0.065 (%)	
and Combustion Science 2007, 33[3], 233-271.		Diesel			Steady State		200 - 1700 (ppm)		365 - 690 (ppm)	0.03 - 0.058 (%)	
Agarwal, D.; Sinha, S.; Agarwal, A. K. Experimental investigation of control of		B10 Rice Bran Oil	LD	Genset	Constant Speeds with varying EGR %	EGR	50 - 155 (ppm)		850 - 3100 (ppm)	200 - 730 (ppm)	
compression ignition Engine. Renewable Energy 2006, 31 (14), 2356-2369.		Diesel	LD	Genset	Constant Speeds with varying EGR %	EGR	65 - 200 (ppm)		1200 - 3000 (ppm)	175 - 625 (ppm)	
Altun, S.; Bulut, H.; Oner, C. The comparison of Engine performance and exhaust emission characteristics of		B50 Sesame	Test Engine	Engine Dyno.	Constant Speeds		175 - 800 (ppm)			150 - 250 (ppm)	
sesame oil-diesel fuel mixture with diesel fuel in a direct injection diesel Engine. Renewable Energy 2008, 33 (8), 1791- 1795.		Diesel	Test Engine	Engine Dyno.	Constant Speeds		350 - 780 (ppm)			350 - 600 (ppm)	
Arai, M.; Saito, T.; Furuhata, T. Effect of biodiesel fuel on direct injection diesel Engine performance. Journal of Propulsion and Power 2008, 24 (3), 603- 608.		B20 Palm Oil	Test Engine	Engine Dyno.	Constant speed with excess air ratios		1000 - 1400 (ppm)	.5 - 1.2 (g/kWh)		~0 (ppm)	6 - 10
		B100 Rubber seed oil	Test Engine	Engine Dyno.	Constant Speed		500 - 2150 (ppm)			.0348 (% vol.)	
Baiju, B.; Das, L. M.; Gajendra Babu, M. K. Experimental Investigations on a Rubber seed oil Methyl Ester Fueled		B20 Rubber seed oil	Test Engine	Engine Dyno.	Constant Speed		500 - 2550 (ppm)			.0363 (% vol.)	
Compression Ignition Engine. SAE International 2008, 2008-28-0073, 505- 513.		B10 Rubber seed oil	Test Engine	Engine Dyno.	Constant Speed		500 - 2520 (ppm)			.0373 (% vol.)	
		Diesel	Test Engine	Engine Dyno.	Constant Speed		475 - 2100 (ppm)			.0383 (% vol.)	
Ballesteros, R.; Hernandez, J. J.; Lyons, L. L.; Cabanas, B.; Tapia, A. Speciation of the semivolatile hydrocarbon Engine emissions from sunflower biodiesel. Fuel 2008, 87 (10-11), 1835-1843.		B100 Sunflower	LD	Chassis Dyno.	European Emission Directive 70/220 (Extra Urban and Urban mode)	Fixed EGR		.0324 (g/kWh)	.00207 (g/kWh)		

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
Banapurmath, N. R.; Tewari, P. G.; Hosmath, R. S. Experimental investigations of a four-stroke single cylinder direct injection diesel Engine operated on dual fuel mode with producer		B100 Honge Oil	Test Engine	Engine Dyno.	Constant Speed		900 - 550 (ppm)			.4285 (%)	
gas as inducted fuel and Honge oil and its methyl ester (HOME) as injected fuels. Renewable Energy 2008, 33 (9), 2007- 2018.		Diesel	Test Engine	Engine Dyno.	Constant Speed		110 - 1250 (ppm)		18 - 65 (ppm)	0.04 - 0.19 (%)	
Banapurmath, N. R.; Tewari, P. G.; Hosmath, R. S. Performance and		B100 Pongamia	Test Engine	Engine Dyno.	Constant Speed		100 - 1050 (ppm)		27 - 82 (ppm)	.0632 (%)	
emission characteristics of a DI compression ignition Engine operated on Honge, Jatropha and sesame oil methyl		B100 Jatropha	Test Engine	Engine Dyno.	Constant Speed		140 - 1000 (ppm)		25 - 87 (ppm)	.074 (%)	
esters. Renewable Energy 2008, 33 (9), 1982-1988.		B100 Sesame	Test Engine	Engine Dyno.	Constant Speed		120 - 1070 (ppm)		22 - 77 (ppm)	.0528 (%)	
		B10 Pongamia Oil	Test Engine	Engine Dyno.	Constant Speed		1130 - 1160 (ppm)		50 - 55 (ppm)	0.3 - 0.38 (%)	
Basavaraja, T.; Reddy, R. P.; Swamy, V.		B20 Pongamia Oil	Test Engine	Engine Dyno.	Constant Speed		1030 - 1120 (ppm)		43 - 52 (ppm)	0.27 - 0.33 (%)	
Effect of Injection Pressure on Emission Performance of Bio-diesel and its Blends. Automotive Research Association of India 2005, 467-473.		B40 Pongamia Oil	Test Engine	Engine Dyno.	Constant Speed		1050 - 1165 (ppm)		53 - 63 (ppm)	0.3 - 0.4 (%)	
		B100 Pongamia Oil	Test Engine	Engine Dyno.	Constant Speed		1125 - 1185 (ppm)		52 - 60 (ppm)	0.36 - 0.42 (%)	
		Diesel	Test Engine	Engine Dyno.	Constant Speed		1040 - 1110 (ppm)		65 - 72 (ppm)	0.48 - 0.6 (%)	
		B20 Soy	HD	Off-Road	Constant Load and Speed	US Tier 2 emissions guidelines	584 (ppm)	0.04 - 0.06 (g/kWh)	130 (ppm)	81.4 (ppm)	8.25 (%)
Bennett, M.; Volckens, J.; Stanglmaier, R.; McNichol, A. P.; Ellenson, W. D.; Lewis, C. W. Biodiesel effects on particulate		B29 Soy	HD	Off-Road	Constant Load and Speed	US Tier 2 emissions guidelines	551(ppm)	.0304 (g/kWh)	104 (ppm)	83.3 (ppm)	8.05 (%)
diesel Engine. Journal of Aerosol Science 2008, 39 (8), 667-678.		B83 Soy	HD	Off-Road	Constant Load and Speed	US Tier 2 emissions guidelines	596 (ppm)	.0204 (g/kWh)	64.3 (ppm)	80.2 (ppm)	8.3 (%)
		Diesel	HD	Off-Road	Constant Load and Speed	US Tier 2 emissions guidelines	575 - 583 (ppm)		120 - 132 (ppm)	87 - 93 (ppm)	8.16 (%)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
Bhardwaj; O.; Abraham, M. A		B10 Jatropha and B10 Karanja	MD	Chassis Dyno.		Diesel Oxidation Catalyst and EGR	0.45 (gm/km)	0.9 (gm/km)	0.13 (gm/km)	0.48 (gm/km)	
Comparative Study of Performance and Emission Characteristics of a CRDe SUV Fueled With Biodiesel Blends and Diesel Fuel. SAE International 2008, 2008-28- 0075, 520-529.		B20 Jatropha and B20 Karanja	MD	Chassis Dyno.		Diesel Oxidation Catalyst and EGR	0.46 (gm/km)	0.8 (gm/km)	0.12 (gm/km)	0.44 (gm/km)	
		Diesel	MD	Chassis Dyno.		Diesel Oxidation Catalyst and EGR	0.18 (gm/km)	0.10 (gm/km)	0.17 (gm/km)	0.60 (gm/km)	
		B5 Rapeseed	LD	Engine Dyno.	Elementary ECE (UDC) driving cycle	turbo	0.38 (g/km)	.010 (g/km)	0.07 (g/km)	0.78 (g/km)	145 (g/km)
Bielaczyc, P.; Szczotka, A. A Study of RME-Based Biodiesel Blend Influence on		B20 Rapeseed	LD	Engine Dyno.	Elementary ECE (UDC) driving cycle	turbo	0.37 (g/km)	.0095 (g/km)	0.075 (g/km)	0.85 (g/km)	145 (g/km)
RME-Based Biodiesel Blend Influence on Performance, Reliability and Emissions from Modern Light-Duty Diesel Engines. SAE International 2008.		B30 Rapeseed	LD	Engine Dyno.	Elementary ECE (UDC) driving cycle	turbo	0.37 (g/km)	.008 (g/km)	0.085 (g/km)	0.92 (g/km)	150 (g/km)
		Diesel	LD	Engine Dyno.	Elementary ECE (UDC) driving cycle	turbo	0.37 (g/km)	.010 (g/km)	0.080 (g/km)	0.90 (g/km)	140 (g/km)
		B100 Lard					3% increase from diesel				
		B100 tallow					1.8 - 2%				
Biodiesel Handling and Use Guide; DOE/G0-102006-2358; Sep, 06.		B100 Yellow Grease					2.5 - 5.5%				
		B100 Canola					12%				
		B100 Soy bean oil					15%				
Cheng, C. H.; Cheung, C. S.; Chan, T. L.; Lee, S. C.; Yao, C. D.; Tsang, K. S. Comparison of emissions of a direct		B100 Waste Cooking Oil	MD	Engine Dyno.	Constant speed with differing loads		6.4 - 11.8 (g/kWh)	.5x10 ⁴ - 4x10 ⁴ (ug/m ³)	. 5 - 5 (g/kWh)	1 - 17 (g/kWh)	750 - 1800 (g/kWh)
injection diesel Engine operating on biodiesel with emulsified and fumigated methanol. Fuel 2008, 87 (10-11), 1870- 1879.		Diesel	MD	Engine Dyno.	Constant speed with differing loads		5.8 - 11.2 (g/kWh)	.7x10 ⁴ - 8.3x10 ⁴ (ug/m ³)	2 - 8 (g/kWh)	2 - 20 (g/kWh)	800 - 1800 (g/kWh)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Cho, H. M.; Maji, S.; Pathak, B. D. Waste		B100 Waste cooking oil	LD	Electrical Generator	Constant Loads		100 - 2500 (ppm)		22 - 40 (ppm)		
SAE International 2008, 2008-28-0013.		Diesel	LD	Electrical Generator	Constant Loads		100 - 2000 (ppm)		45 - 65 (ppm)		
	1988	B100	HD	Chassis Dyno.	Federal Test Procedure	None	6.3 (g/mi)	425 (mg/mi)	.32 (g/mi)	1.35 (g/mi)	
	1988	B20	HD	Chassis Dyno.	Federal Test Procedure	None	7.0 (g/mi)	400 (mg/mi)	.33 (g/mi)	1.30 (g/mi)	
	1990	B100	HD	Chassis Dyno.	Federal Test Procedure	None	6.3 (g/mi)	480 (mg/mi)	1.12 (g/mi)	2.20 (g/mi)	
Durbin, T. D.; Collins, J. R.; Norbeck, J.	1990	B20	HD	Chassis Dyno.	Federal Test Procedure	None	7.0 (g/mi)	850 (mg/mi)	.73 (g/mi)	2.25 (g/mi)	
Durbin, T. D.; Collins, J. R.; Norbeck, J. M.; Smith, M. R. Effects of biodiesel, biodiesel blends, and a synthetic diesel on emissions from light heavy-duty diesel vehicles. Environmental Science & Technology 34[3], 349-355. 2000.	1995	B100	HD	Chassis Dyno.	Federal Test Procedure	Oxidation Catalyst	6.2 (g/mi)	110 (mg/mi)	.50 (g/mi)	1.90 (g/mi)	
	1995	B20	HD	Chassis Dyno.	Federal Test Procedure	Oxidation Catalyst	6.5 (g/mi)	120 (mg/mi)	.22 (g/mi)	1.75 (g/mi)	
	1996	B100	HD	Chassis Dyno.	Federal Test Procedure	Oxidation Catalyst	8.5 (g/mi)	75 (mg/mi)	.33 (g/mi)	1.60 (g/mi)	
	1996	B20	HD	Chassis Dyno.	Federal Test Procedure	Oxidation Catalyst	8.4 (g/mi)	80 (mg/mi)	.28 (g/mi)	1.62 (g/mi)	
	1988 - 1996	Diesel	HD	Chassis Dyno.	Federal Test Procedure	Oxidation Catalyst	6.25 - 8.25 (g/mi)	75 - 350 (mg/mi)	0.35 - 0.92 (g/mile)	1.45 - 2.25 (g/mi.)	
	1983- 1993	B20 Soy Gold (Soybean Oil)	HD	Chassis Dyno.	Steady State		1.9 - 10 (g/mi)	160 - 960 (mg/mi.)	.15 - 1.3 (g/mi)	.9 - 7.7 (g/mi.)	
Durbin, T. D.; Norbeck, J. M. The Effects of Biodiesel Blends and ARCO EC-Diesel on Emissions from Light Heavy-Duty Diesel Vehicles; CE-CERT: 02.	1983- 1993	B20 OXyG B-60 (Yellow Grease)	HD	Chassis Dyno.	Steady State		2.0 - 9.2 (g/mi.)	170 - 640 (mg/mi)	.15 - 1.0 (g/mi.)	0.8 - 6.0 (g/mi.)	
	1983- 1993	Diesel	HD	Chassis Dyno.	Steady State		2 - 8.7 (g/mi.)	125 - 600 (g/mile)	0.10 - 1.30 (g/mile)	0.70 - 7.50 (g/mile)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
		B100 Linseed	HD		Steady State		4.9 - 5.1 (g/hp-hr)	.0508 (g/hp-hr)		.04 - 1.3 (g/hp-hr)	
Fanick, E. R. Diesel Fuel Keeping Pace with Diesel Engine Technology. SAE International 2008, 2008-01-1808		B20 Linseed	HD		Steady State		4.7 - 4.9 (g/hp-hr)	.0911 (g/hp-hr)		0.7 - 1.6 (g/hp-hr)	
		Diesel	HD		Steady State		4.6 - 4.7 (g/hp-hr)	0.1 - 0.125 (g/hp-hr)		0.75 - 2.05 (g/hp-hr)	
		B100 Jatropha	Test Engine	Engine Dyno.	Constant Speed		550 - 825 (ppm)		185 - 295 (ppm)	0.30 - 0.50 (% vol)	
Fernando Contadini, J.; Moore, R. M.; Sperling, D.; Sundaresan, M. Life-Cycle		B75 Jatropha	Test Engine	Engine Dyno.	Constant Speed		550 - 815 (ppm)		210 - 380 (ppm)	0.40 - 0.50 (% vol.)	
Transportation: Dealing with Uncertanties. SAE International 2000, 2000-01-0597.		B50 Jatropha	Test Engine	Engine Dyno.	Constant Speed		545 - 800 (ppm)		230 - 425 (ppm)	0.40 - 0.50 (% vol.)	
		Diesel	Test Engine	Engine Dyno.	Constant Speed		550 - 785 (ppm)		235 - 460 (ppm)	0.30 - 0.60 (% vol.)	
	1991	B20 Soy bean Oil	HD		40 CFR Part 86 Subpart N		4.627 - 5.119 (g/bhp-h)	0.221 (g/bhp-h)	0.031 - 0.113 (g/bhp-h)	2.747 - 4.854 (g/bhp-h)	564 - 567 (g/bhp-h)
	1991	B20 Tallow	HD		40 CFR Part 86 Subpart N		4.510 (g/bhp-h)	0.066 - 0.236 (g/bhp-h)	0.069 (g/bhp-h)	4.986 (g/bhp-h)	586 (g/bhp-h)
Graboski, M. S.; McCormick, R. L.;	1991	B100 Canola	HD		40 CFR Part 86 Subpart N		5.178 (g/bhp-h)	0.081 (g/bhp-h)	0.069 (g/bhp-h)	3.129 (g/bhp-h)	572 (g/bhp-h)
Alleman, T. L.; Herring, A. M. The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Diesel Engine, Final Report: Report 2 in a series	1991	B100 Lard	HD		40 CFR Part 86 Subpart N		4.765 (g/bhp-h)	0.072 (g/bhp-h)	0.077 (g/bhp-h)	2.660 (g/bhp-h)	585 (g/bhp-h)
of 6. NREL 2003.	1991	B100 tallow	HD		40 CFR Part 86 Subpart N		4.692 - 4.712 (g/bhp-h)	0.067 - 0.071 (g/bhp-h)	0.059 - 0.068 (g/bhp-h)	2.725 - 2.978 (g/bhp-h)	561 - 566 (g/bhp-h)
	1991	Diesel	HD		40 CFR Part 86 Subpart N		4.586 (g/bhp-h)	0.263 (g/bhp-h)	0.105 (g/bhp-h)	5.521 (g/bhp-h)	568 (g/bhp-h)
		B20 Soy Bean Oil	Various HD 2- Stroke	On Road	Regular driving conditions		4.25 - 12.11 (g/bhp-hr)	0.11 - 0.81 (g/bhp-hr)	0.12 - 1.43 (g/bhp-hr)	0.45 - 2.73 (g/bhp-hr)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
		B30 Soy Bean Oil	Various HD 2- Stroke	On Road	Regular driving conditions		4.78 - 10.7 (g/bhp-hr)	0.173 - 0.258 (g/bhp-hr)	0.29 - 0.54 (g/bhp-hr)	1.03 - 1.69 (g/bhp-hr)	
		B40 Soy Bean Oil	Various HD 2- Stroke	On Road	Regular driving conditions		4.86 - 4.89 (g/bhp-hr)	0.162 - 0.258 (g/bhp-hr)	0.38 - 0.43 (g/bhp-hr)	0.95 - 1.07 (g/bhp-hr)	
		B10 Soy Bean Oil	Various HD 2- Stroke	On Road	Regular driving conditions		4.38 - 4.97 (g/bhp-hr)	0.186 - 0.286 (g/bhp-hr)	0.53 - 0.72 (g/bhp-hr)	1.43 - 2.33 (g/bhp-hr)	
		B100 Soy Bean Oil	Various HD 2- Stroke	On Road	Regular driving conditions		5.79 (g/bhp- hr)	0.152 (g/bhp-hr)	0.12 (g/bhp-hr)	0.87 (g/bhp-hr)	
Graboski, M. S.; McCormick, R. L.; Alleman, T. L.; Herring, A. M. The Effect of Biodiesel Composition on Engine		B10 Rapeseed Oil	Various HD 2- Stroke	On Road	Regular driving conditions		5.81 (g/bhp- hr)	0.243 (g/bhp-hr)	0.376 (g/bhp-hr)	1.02 (g/bhp-hr)	
Emissions from a DDC Series 60 Diesel Engine, Final Report: Report 2 in a series of 6. NREL 2003.		B20 Rapeseed Oil	Various HD 2- Stroke	On Road	Regular driving conditions		5.54 - 5.87 (g/bhp-hr)	0.238 - 0.257 (g/bhp-hr)	0.363 - 0.467 (g/bhp-hr)	1.04 - 1.20 (g/bhp-hr)	
		B40 Rapeseed Oil	Various HD 2- Stroke	On Road	Regular driving conditions		5.82 (g/bhp- hr)	0.244 (g/bhp-hr)	0.346 (g/bhp-hr)	0.95 (g/bhp-hr)	
		B100 Rapeseed Oil	Various HD 2- Stroke	On Road	Regular driving conditions		5.61 (g/bhp- hr)	0.164 (g/bhp-hr)	0.09 (g/bhp-hr)	0.81 (g/bhp-hr)	
		B20 Tallow	Various HD 2- Stroke	On Road	Regular driving conditions		4.01 - 4.7 (g/bhp-hr)	0.22 - 0.254 (g/bhp-hr)	0.37 - 0.38 (g/bhp-hr)	1.49 - 1.8 (g/bhp-hr)	
		Diesel	Various HD 2- Stroke	On Road	Regular driving conditions		4.4 - 11.72 (g/bhp-hr)	0.20 - 0.83 (g/bhp-hr)	0.29 - 2.01 (g/bhp-hr)	0.71 - 3.59 (g/bhp-hr)	
Guo H. Shenghua L. Longhao Z.		B100 Peanut Oil Monoester	Test Engine	Engine Dyno.	Steady State		350 - 1400 (x10 ⁻⁶)		3 - 7 (x10 ⁻ ⁶)	.0117 (%vol.)	
Dayong, J. Study on Ethylene Glycol Monomethyl Ether Peanut Oil Monoester as a Novel Bodiesel. SAE International		B50 Peanut Oil Monoester	Test Engine	Engine Dyno.	Steady State		350 - 1300 (x10 ⁻⁶)		5.5 - 9.5 (x10 ⁻⁶)	.01 - 0.2 (% vol.)	
2008, 2008-01-1575.		Diesel	Test Engine	Engine Dyno.	Steady State		375 - 1550 (ppm)		7 - 13 (ppm)	0.02 - 0.23 (% vol.)	
Hasegawa, M.; Sakurai, Y.; Kobayashi, Y.; Oyama, N.; Sekimoto, M.; Watanabe, H. Effects of Fuel Properties (Content of		B100 Rape seed Oil	HD	Chassis Dyno.	JC08, JE05	EGR, DOC, DPD	1.65 - 1.70 (g/km)	0.002 (g/km)	0.02 - 0.03 (g/km)		

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
FAME or GTL) on Diesel Emissions under Various Driving Modes. SAE International 2007, 2007-01-4041.		B100 Palm Oil	HD	Chassis Dyno.	JC08	EGR, DOC, DPD	1.55 - 1.60 (g/km)	0.002 (g/km)	0.01 - 0.02 (g/km)		
		B100 Soy Bean Oil	HD	Chassis Dyno.	JC08	EGR, DOC, DPD	1.70 - 1.75 (g/km)	0.002 (g/km)	0.02 - 0.03 (g/km)		
		Diesel	HD	Chassis Dyno.	JC08	EGR, DOC, DPD	1.40 - 1.65 (g/km)	0.002 (g/km)	0.03 - 0.05 (g/km)		
Hribernik, A.; Kegl, B. Influence of		B100	LD turbo	Engine Dyno.	Constant Speeds		6.1 - 7.1 (g/kWh)		0.9 - 1.3 (g/kWh)	0.5 - 4.0 (g/kWh)	
biodiesel fuel on the combustion and emission formation in a direct injection (DI) diesel Engine. Energy & Fuels 2007,		B100	MD	Engine Dyno.	Constant Speeds		6.6 - 12.6 (g/kWh)		0.1 - 0.2 (g/kWh)	0.6 - 1.6 (g/kWh)	
21 (3), 1760-1767.		Diesel	MD	Engine Dyno.	Constant Speeds		6.6 - 12.6 (g/kWh)		0.2 - 2.2 (g/kWh)	0.5 - 2.1 (g/kWh)	
Ilkilic, C. The effect of sunflower oil methyl ester and diesel fuel blend on the performance of a diesel Engine. Energy		B75 Sunflower	Test Engine	Engine Dyno.	Constant Speeds		900 - 1300 (ppm)			650 - 2750 (ppm)	7 - 8 (%)
Sources Part A-Recovery Utilization and Environmental Effects 2008, 30 (19), 1761-1770.		Diesel	Test Engine	Engine Dyno.	Constant Speeds		1100 - 1600 (ppm)			1300 - 4000 (ppm)	7 - 11 (%)
Kass, M. D.; Lewis, S. A.; Swartz, M. M.; Huff, S. P.; Lee, D. W.; Wagner, R. M.; Storey, J. M. E. Utilizing Water- Emulsification to Reduce NOx and		86.5% B100, 10% Water, 3.5% Surfactant	LD		Fixed speed with varying EGR	Dual EGR	0.4 - 7.1 (g/hp-h)	2.0 - 6.0 (g/hp-h)	0.4 - 0.6 (g/hp-h)	1.3 - 3.6 (g/hp-h)	5.6 - 10 (g/hp-h)
Particulate Emissions Associated with Biodiesel; 07.		B100 Soybean Oil	LD		Fixed speed with varying EGR	Dual EGR	0.7 - 6.8 (g/hp-h)	2.0 - 7.0 (g/hp-h)	0.1 - 0.2 (g/hp-h)	0.8 - 2.0 (g/hp-h)	6.0 - 10.4 (g/hp-h)
Kaufman, J. Renewable Diesel. 2007.		B20 Conoco Phillips (Soy)					-7.70%	-9%	-50%	-36%	
Kawano, D.; Ishii, H.; Goto, Y.; Noda, A. Optimization of Engine System for		B100 Rapeseed Oil	LD		Steady State	EGR, NSR (Nox Storage Reduction Catalyst), DPNR, OC	0.6 - 1.5 (g/kWh)		.02503 (g/kWh)	.1152 (g/kWh)	
International 2007, JSAE 20077256 (SAE 2007-01-2028), 1254-1260.		Diesel	LD		Steady State	EGR, NSR (Nox Storage Reduction Catalyst), DPNR, OC	0 - 1.0 (g/kWh)				

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Kegl, B. Effects of biodiesel on emissions of a bus diesel Engine. Bioresource Technology. 2007.		B100 Rapeseed	HD	Engine Dyno.	Constant Speeds (ESC test)		-1060 % change		-2560 % change	-60 - 30 % change	
Kegl, B. Experimental investigation of optimal timing of the diesel Engine		B100 Rapeseed	HD	Engine Dyno.	Constant Speeds	Direct Injection M system	800 - 2750 (ppm)		50 - 100 (ppm)	150 - 600 (ppm)	
injection pump using biodiesel fuel. Energy & Fuels 2006, 20 (4), 1460-1470.		Diesel	HD	Engine Dyno.	Constant Speeds	Direct Injection M system	800 - 1700 (ppm)		50 - 100 (ppm)	100 - 700 (ppm)	
Kegl, B. NOx and particulate matter (PM) emissions reduction potential by biodiesel		B100 Soy Bean Oil	HD	Engine Dyno.	13 modes of European stationary cycle test		75 - 2400 (ppm)		30 - 110 (ppm)	120 - 810 (ppm)	
usage. Energy & Fuels 2007, 21, 3310- 3316.		Diesel	HD	Engine Dyno.	13 modes of European stationary cycle test		125 - 2200 (ppm)		42 - 160 (ppm)	170 - 800 (ppm)	
Kerihuel; Kumar, M. S.; Bellettre, J.; Tazerout, M. Investigations on a CI Engine Using Animal Fat and its Emulsions With Water and Methanol as Fuel. SAE International 2005, 2005-01- 1729.		B100 Animal Fat	Test Engine	Engine Dyno.	Differing Loads				.19 - 0.8 (g/kWh)	1.0 - 26 (g/kWh)	7.0 - 18.5 (g/kWh)
Keskin, A.; Guru, M.; Altiparmak, D. Biodiesel production from tall oil with synthesized Mn and Ni based additives:		B60 Tall Oil	Test Engine	Electrical Dyno.	Constant Speeds		190 - 420 (ppm)			350 - 1900 (ppm)	
Effects of the additives on fuel consumption and emissions. Fuel 2007, 86 (7-8), 1139-1143.		Diesel	Test Engine	Electrical Dyno.	Constant Speeds		230 - 380 (ppm)			600 - 2900 (ppm)	
Kim, M. Y.; Yoon, S. H.; Hwang, J. W.; Lee, C. S. Characteristics of Particulate		B100 Soybean	Test Engine	Engine Dyno.	Constant Speed		2.0 - 8.0 (g/kWh)		.1315 (g/kWh)	2.3 - 3.5 (g/kWh)	
Every of the induced and the induced of the induced		Diesel	Test Engine	Engine Dyno.	Constant Speed		2.0 - 8.0 (g/kWh)		0.13 - 0.15 (g/kWh)	2.0 - 3.5 (g/kWh)	
Engine Division 2007 Fall Technical Conference 2007, ICEF2007-1715, 1-7.		B100 Soybean Oil	Test Engine	Engine Dyno.	Constant Speeds		3 - 8 (g/kWh)		.0506 (g/kWh)	.5 - 2.0 (g/kWh)	
		B100 Coconut Oil	Test Engine	Engine Dyno.	Constant Loads		190 - 1100 (ppm)		17 - 40 (ppm)	200 - 415 (ppm)	
Kinoshita, E.; Myo, T.; Hamasaki, K.; Nishi, S. Combustion Characteristics of		B100 Palm Oil	Test Engine	Engine Dyno.	Constant Loads		200 - 1150 (ppm)		20 - 45 (ppm)	210 - 400 (ppm)	
Ester. SAE International 2007, JSAE 20077065.		B100 Rapeseed Oil	Test Engine	Engine Dyno.	Constant Loads		200 - 1225 (ppm)		23 - 56 (ppm)	225 - 660 (ppm)	
		Diesel	Test Engine	Engine Dyno.	Constant Loads		190 - 1200 (ppm)		32 - 73 (ppm)	220 - 560 (ppm)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
		B100 Waste Cooking Oil	LD	Hydraulic Dyno.	Full Load at Various speeds	Turbo	410 - 465 (ppm)			75 - 675 (ppm)	7 - 10.2 (%)
Kocak, M. S.; Ileri, E.; Utlu, Z. Experimental study of emission		B100 Canola	LD	Hydraulic Dyno.	Full Load at Various speeds	Turbo	415 - 470 (ppm)			75 - 720 (ppm)	6.2 - 10.0 (%)
from canola, hazelnut, and waste cooking oils. Energy & Fuels 2007, 21, 3622-3626.		B100 Hazelnut Oil	LD	Hydraulic Dyno.	Full Load at Various speeds	Turbo	410 - 460 (ppm)			75 - 675 (ppm)	7.2 - 10.0 (%)
		Diesel	LD	Hydraulic Dyno.	Full Load at Various speeds	Turbo	410 - 485 (ppm)			100 - 875 (ppm)	8.0 - 10.7 (%)
Korros D. M.: Karonis D.: Lois E.: Linek		B20 Animal Fat	Test Engine	Electrical Generator	Constant Speed		8 % change	-13 % change			
M. B.; Gupta, A. K. Aviation fuel JP-5 and biodiesel on a diesel Engine. Fuel 2008,		B60 Animal Fat	Test Engine	Electrical Generator	Constant Speed		13 % change	-22 % change			
07, 70-70.		B100 Animal Fat	Test Engine	Electrical Generator	Constant Speed		15 % change	-27 % change			
Krahl, J.; Munack, A.; Ruschel, Y.; Schroder, O.; Bunger, J. Comparison of Emissions and Mutagenicity from		B100 Rapeseed Oil	LD	Engine Dyno.	ESC		5.6 (g/kWh)	.03 (g/kWh)		0.26 (g/kWh)	
Biodiesel, Vegetable Oil, GTL and Diesel Fuel. SAE International 2007.		Diesel	LD	Engine Dyno.	ESC		4.8 (g/kWh)	0.07 (g/kWh)		0.55 (g/kWh)	
		B100 Karanja	Test Engine	Electric Generator	Constant Speed, varying load		22 - 54 (g/kWh)		0.18 - 0.38 (g/kWh)	1.0 - 7.0 (g/kWh)	
Kumar, C.; Gajendra Babu, M. K.; Das, L. M. Experimental Investigations on a		B60 Karanja	Test Engine	Electric Generator	Constant Speed, varying load		24 - 45 (g/kWh)		0.16 - 0.64 (g/kWh)	2.0 - 11.0 (g/kWh)	
Engine. SAE International 2006, 2006-01- 0238.		B20 Karanja	Test Engine	Electric Generator	Constant Speed, varying load		20 - 42 (g/kWh)		0.11 - 0.55 (g/kWh)	2.5 - 17.0 (g/kWh)	
		Diesel	Test Engine	Electric Generator	Constant Speed, varying load		19 - 52 (g/kWh)		0.15 - 0.54 (g/kWh)	3.0 - 28 (g/kWh)	
Kuronen, M.; Mikkonen, S.; Aakko, P.; Murtonen, T. Hydrotreated Vegetable Oil	2007	B100 Hydro- treated Veg. oil	HD	On Road	Braunschweig	SCR	-8 % change	-30 % change		-6 % change	
as Fuel for Heavy Duty Diesel Engines. SAE International 2007, 2007-01-4031.	2007	B100 Hydro- treated Veg. oil	HD	On Road	Braunschweig	EGR	-10 % change	-46 % change		-50 % change	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Lapuerta, M.; Armas, O.; Ballesteros, R.; Fernandez, J. Diesel emissions from biofuels derived from Spanish potential vegetable oils. Fuel 2005, 84 (6), 773-780.		B25 Cyrana Oil	LD	Hydraulic Brake	Transient cycle 70/220 amendment 2001/C 240 E/01	Turbo, intercooler	450 - 2250 (mg/kWh)	0.2 - 0.6 (g/kWh)	0.1026 (g/kWh)		
		B100 Cyrana Oil	LD	Hydraulic Brake	Transient cycle 70/220 amendment 2001/C 240 E/01	Turbo, intercooler	700 - 2100 (mg/kWh)	0.22 - 0.25 (g/kWh)	0.08 - 0.16 (g/kWh)		
		B25 Sunflower Oil	LD	Hydraulic Brake	Transient cycle 70/220 amendment 2001/C 240 E/01	Turbo, intercooler	200 - 2050 (mg/kWh)	0.35 - 0.7 (g/kWh)	0.18 - 0.78 (g/kWh)		
		B100 Sunflower Oil	LD	Hydraulic Brake	Transient cycle 70/220 amendment 2001/C 240 E/01	Turbo, intercooler	500 - 2250 (mg/kWh)	0.22 - 0.42 (g/kWh)	0.15 - 0.12 (g/kWh)		
		Diesel	LD	Hydraulic Brake	Transient cycle 70/220 amendment 2001/C 240 E/01	Turbo, intercooler	550 - 2300 (mg/kWh)	0.37 - 1.13 (g/kWh)	0.2 - 0.76 (g/kWh)		
Lapuerta, M.; Herreros, J. M.; Lyons, L. L.; Garcia-Contreras, R.; Briceno, Y. Effect of the alcohol type used in the production of waste cooking oil biodiesel on diesel performance and emissions. Fuel 2008, 87 (15-16), 3161-3169.		B70 Waste Cooking Oil	LD	Chassis Dyno.	European Driving Cycle (C,F,G,H,U10)	EGR only	4.5 - 5.5 (g/kWh)	.0607 (g/kWh)	.0833 (g/kWh)		
		B100 Waste Cooking Oil	LD	Chassis Dyno.	European Driving Cycle (C,F,G,H,U10)	EGR only	4.3 - 5.3 (g/kWh)	.0506 (g/kWh)	.0308 (g/kWh)		
		B30 Waste Cooking Oil	LD	Chassis Dyno.	European Driving Cycle (C,F,G,H,U10)	EGR only	4 - 5.7 (g/kWh)	.06 - 1.0 (g/kWh)			
		Diesel	LD	Chassis Dyno.	European Driving Cycle (C,F,G,H,U10)	EGR only	4 - 5.7 (g/kWh)	0.07 - 0.14 (g/kWh)	0.06 - 0.40 (g/kWh)		
Lea-Langton, A.; Li, H.; Andrews, G. E. Comparison of Particulate PAH Emissions for Diesel, Biodiesel adn Cooking Oil using a Heavy Duty DI Diesel Engine. SAE International 2008, 2008-01-1811.	1999	B100 Waste Cooking Oil	HD	Generator	Steady State	Oxidation Catalyst (Euro 2)	6.5 - 8.0 (g/kWh)	.02507 (g/kWh)	.25 - 0.6 (g/kWh)	0.2 - 1.6 (g/kWh)	
	1999	B100 Rapeseed	HD	Generator	Steady State	Oxidation Catalyst (Euro 2)	7.8 - 8.0 (g/kWh)	.02207 (g/kWh)	.28 - 0.8 (g/kWh)	0.8 - 3.0 (g/kWh)	
	1999	B100 Rapeseed	HD	Generator	Steady State	Oxidation Catalyst (Euro 2)	6.0 - 8.1 (g/kWh)		.55 - 1.2 (g/kWh)	2.2 - 6.5 (g/kWh)	
Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO ₂
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Lebedevas, S.; Vaicekauskas, A.;		B100 Rapeseed oil		hydraulic brake	Steady state		13 - 14 (g/kWh)				3.2 - 9.0 (%)
Lebedeva, G.; Makareviciene, V.; Janulis, P.; Kazancev, K. Use of waste fats of animal and vegetable origin for the production of biodiesel fuel: Quality, motor properties, and emissions of harmful components. Energy & Fuels 20[5], 2274- 2280, 2006		60% Rapeseed oil, 32% Palm Oil, 8% Linseed Oil		hydraulic brake	Steady state		13 - 13.5 (g/kWh)				3.5 - 9.0 (%)
2200. 2000.		Diesel		hydraulic brake	Steady state		12 (g/kWh)				3.5 - 9.3 (%)
Leung, D. Y. C.; Luo, Y.; Chan, T. L. Optimization of exhaust emissions of a diesel Engine fuelled with biodiesel. Energy & Fuels 2006, 20 (3), 1015-1023.			Test Engine		Varying Engine settings		450 - 1150 (ppm)		107 - 130 (ppm)		
	1999	B100 Rapeseed	HD		Steady State	Turbo, Oxidation catalyst	392 - 566 (ppm)	0.022 - 0.05 (g/kWh)	33 - 106 (ppm)	12 - 75 (ppm)	3.98 - 5.94 (ppm)
Li, H.; Andrews, G. E.; Balsevich-Prieto, J L. Study of Emission and Combustion Characteristics of RME B100 Biodiesel from a Heavy Duty DI Diesel Engine. SAE International 2007.	1999	Diesel	HD		Steady State	Turbo, Oxidation catalyst	385 - 547 (ppm)	0.032 - 0.06 (g/kWh)	44 - 218 (ppm)	12 - 160 (ppm)	3.50 - 5.91 (ppm)
from a Heavy Duty DI Diesel Engine. SAE International 2007.	1999	B100 Rapeseed	HD		Steady State	Turbo	388 - 560 (ppm)	0.027 - 0.07 (g/kWh)	180 - 181 (ppm)	116 - 167 (ppm)	3.99 - 5.84 (ppm)
	1999	Diesel	HD		Steady State	Turbo	380 - 539 (ppm)	0.043 - 0.08 (g/kWh)	254 - 320 (ppm)	133 - 220 (ppm)	3.60 - 5.83 (ppm)
Lin, Y. C.; Lee, C. F.; Fang, T.		B20 Palm Oil	HD	Engine Dyno.	Steady State			1.07 (mgm ³)	2.2 (ppm)	24.8 (ppm)	6980 (ppm)
distribution from diesel Engines fueled with palm-biodiesel blends and paraffinic		B100 Palm Oil	HD	Engine Dyno.	Steady State			1.37 (mgm ³)	4.7 (ppm)	29.1 (ppm)	6570 (ppm)
2008, 42 (6), 1133-1143.		Diesel	HD	Engine Dyno.	Steady State		49 (ppm)	1.23 mg/m ³	4.8 (ppm)	27.0 (ppm)	6650 (ppm)
Lu, X. C.; Ma, J. J.; Ji, L. B.; Huang, Z. Experimental study on the combustion characteristics and emissions of biodiesel fueled compression ignition Engines with premixed dimethoxymethane.		B100 Soy Bean Oil with Dimethoxy methane	Test Engine	Engine Dyno.	Vary DMM %	EGR	40 - 550 (ppm)		50 - 160 (ppm)	0.02 - 0.32 (%)	
Lu, X.; Ma, J.; Ji, L.; Huang, Z. Simultaneous reduction of NOx emission and smoke opacity of biodiesel-fueled Engines by port injection of ethanol. Fuel 2007, 87, 1289-1296.		B100 and Ethanol	Test Engine	Engine Dyno.	Constant Speed varying Ethanol %		30 - 550 (ppm)		230 - 500 (ppm)	.08 - 0.3 (%)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO ₂
Malhotra, R. K.; Jain, P.; Chopra, A.;		B20 Pongamia	Average	Chassis Dyno.	Indian Driving Cycle			.051 (g/km)		.143 (g/km)	
Blends on Performance and Exhaust Emissions in Passenger Car. Automotive		B20 Jatropha	Average	Chassis Dyno.	Indian Driving Cycle			.053 (g/km)		.141 (g/km)	
482.		Diesel	Average	Chassis Dyno.	Indian Driving Cycle			.065 (g/km)		.178 (g/km)	
		B15	Test Engine	Engine Dyno.	Varying BMEP	EGR	305 - 325 (ppm)			560 (ppm)	
Marques, A.; Monteiro, E.; Moreira, N. A.; Malheir, S. NOx Emissions Reductions in		Diesel	Test Engine	Engine Dyno.	Varying BMEP	EGR	285 - 305 (ppm)			580 (ppm)	
a Biodiesel Engine by Means of EGR Technology. SAE International 2007.		B15	Test Engine	Engine Dyno.	Varying EGR %	EGR	85 - 330 (ppm)			385 - 450 (ppm)	
		Diesel	Test Engine	Engine Dyno.	Varying EGR %	EGR	310 - 350 (ppm)			395 - 500 (ppm)	
Martin, M. L. J.; Prithviraj, D.; Velappan, K. C. Performance and Emission Characteristics of a CI Engine Fueled with		B100 Cottonseed Oil	Test Engine		Constant Speed				12 - 76 (ppm)	0.07 - 0.28 (%)	
Esterified Cottonseed Oil. SAE International 2005, 2005-26-355.		Diesel	Test Engine		Constant Speed				5 - 48 (ppm)	0.05 - 0.18 (%)	
Mazzoleni, C.; Kuhns, H. D.; Moosmüller, H.; Witt, J.; Nussbaum, N. J.; Chang, M C. O.; Parthasarathy, G.; Kumar, S.; Nathagoundenpalayam, K.; Nikolich, G.; Watson, J. G. A case study of real-world tailpipe emissions for school buses using a 20% biodiesel blend. Science of the Total Environment 385, 146-159. 2007.	1983- 2004	B20	HD	On Road	Steady state		20 - 36 (g/kg)	1.1 - 2.1 (g/kg)	1.6 - 5.0 (g/kg)	17 - 40 (g/kg)	
Mbarawa, M. Performance, emission and		B25 Clove Stem Oil	LD	Engine Dyno.	Constant Speeds		200 - 260 (ppm)		7 - 55 (ppm)	0.9 - 1.4 %	10.3 - 12.5 %
economic assessment of clove stem oil- diesel blended fuels as alternative fuels for diesel Engines. Renewable Energy		B50 Clove Stem Oil	LD	Engine Dyno.	Constant Speeds		310 - 460 (ppm)		6 - 52 (ppm)	.45 - 1.15 %	11.4 - 13.8 %
2008, 33 (5), 871-882.		Diesel	LD	Engine Dyno.	Constant Speeds		310 - 450 (ppm)		13 - 72 (ppm)	0.9 - 1.55 (%)	11.4 - 13.8 (%)
McCormick P. L. The Impact of Piodiosol		B20	Various	Chassis Dyno.			-7 - 7 % change				
McCormick, R. L. The Impact of Biodiesel on Pollutant Emissions and Public Health. Inhalation Toxicology 2006, 19 (1033-		B50	Various	Chassis Dyno.			-83 % change				
1039), 1033-1038.		B100	Various	Chassis Dyno.			-12 - 12 % change				

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Reference McCormick, R. L.; Alleman, T. L. Impact of Biodiesel Fuel on Pollutant Emissions from Diesel Engines; NREL: 07. McCormick, R. L.; Alvarez, J. R.; Graboski, M. S.; Tyson, K. S.; Vertin, K. Fuel Additive and Blending Approaches to Reducing NOx Emissions from Biodiesel. SAE Technical Paper Series 2002, 2002-01-1658. McCormick, R. L.; Williams, A.; Ireland, J. Brimhall, M.; Hayes, R. R. Effects of Biodiesel Blends on Vehicle Emissions;NREL/MP-540-40554; Oct 1, 06.	1991	B100	HD		Steady State, varying iodine number		5.7 - 7.3 (g/kWh)	0.7 - 2.5 (g/kWh)			
McCormick, R. L.; Alleman, T. L. Impact of Biodiesel Fuel on Pollutant Emissions from Diesel Engines; NREL: 07.	1991	B20	HD		Steady State, varying iodine number		1 % change	-12 % change	-20 % change	-12 % change	
	1991	B100	HD		Steady State, varying iodine number		10 % change	-48 % change	-67 % change	-48 % change	
McCormick, R. L.; Alvarez, J. R.; Graboski, M. S.; Tyson, K. S.; Vertin, K. Fuel Additive and Blending Approaches to	1991	B20 Soybean Oil	HD		Constant Speeds	CA Code of Reg. Title 13 section 2282	4.3 (g-bhp-h)	0.146 (g- bhp-h)	.005 (g- bhp-h)	3.6 (g- bhp-h)	
Reducing NOx Emissions from Biodiesel. SAE Technical Paper Series 2002, 2002- 01-1658.	1991	B80 Soybean	HD		Constant Speeds	CA Code of Reg. Title 13 section 2282	5.1 (g-bhp-h)	.078 (g- bhp-h)	.006 (g- bhp-h)	3.0 (g- bhp-h)	
	2003	B20	HD	Chassis Dyno.	Steady State		7.22 - 7.96 (g/mile)	.1718 (g/mile)	.0320 (g/mile)	.12 - 3.2 (g/mile)	
	2003	Diesel	HD	TestTest CycleControl SystemNOxPMHCCOSteady State, varying iodine number57-7.3 (grkWh)0.7-2.5 (grkWh)0.7-2.6 (grkWh)-20 % change-12 % changeSteady State, varying iodine number1 % change-12 % (change-20 % change-12 % changeSteady State, varying iodine number1 % change-48 % change-67 % change-48 % changeConstant SpeedsCA Code of Reg. Title 13 section 22824.3 (g-bhp-h)0.146 (g- bhp-h)0.005 (g- bhp-h)3.6 (g- bhp-h)Chassis Dyno.Constant SpeedsCA Code of Reg. Title 13 section 22825.1 (g-bhp-h)0.07 (g- bhp-h)0.006 (g- bhp-h)3.0 (g- bhp-h)Chassis Dyno.Steady State7.22 - 7.96 (grmile)17 - 18 (grmile)0.03 - 20 (grmile)12 - 3.2 (grmile)Chassis Dyno.Steady State6.9 - 7.75 (grmile)0.138 - (grmile)0.138 - (grmile)0.138 - (grmile)Chassis Dyno.Steady State23.1 - 30.3 (grmile)36 - 1.48 (grmile)17 - 45 (grmile)7.84 - (grmile)Chassis Dyno.Steady State9.79 - 10.39 (grmile)0.27 - 33 (grmile)0.37 - (grmile)5.72 - (6.93 (grmile)Chassis Dyno.Steady State9.78 - 9.85 (grmile)0.193 - (grmile)0.373 - (grmile)5.22 - (grmile)Chassis Dyno.Steady State9.78 - 9.83 (grmile)0.023 - (grmil							
	2000	B20	HD	Chassis Dyno.	Steady State		23.1 - 30.3 (g/mile)	.36 - 1.48 (g/mile)	.1745 (g/mile)	7.58 - 24.49 (g/mile)	
McCormick R L · Williams A · Ireland J ·	2000	Diesel	HD	Chassis Dyno.	Steady State		22.27 - 29.65 (g/mile)	0.4826 - 1.83 (g/mile)	0.20 - 0.536 (g/mile)	8.14 - 27.41 (g/mile)	
Brimhall, M.; Hayes, R. R. Effects of Biodiesel Blends on Vehicle Emissions;NREL/MP-540-40554; Oct 1,	2004	B20	HD	Chassis Dyno.	Steady State		9.79 - 10.39 (g/mile)	.2053 (g/mile)	.3043 (g/mile)	5.72 - 6.93 (g/mile)	
06.	2004	Diesel	HD	Chassis Dyno.	Steady State		9.78 - 9.85 (g/mile)	0.193 - 0.695 (g/mile)	0.373 - 0.439 (g/mile)	5.22 - 8.95 (g/mile)	
	2006	B20	HD	Chassis Dyno.	Steady State		7.64 - 9.14 (g/mile)	.0012 - .0017 (g/mile)	.021 - .031 (g/mile)	.0612 (g/mile)	
	2006	Diesel	HD	Chassis Dyno.	Steady State		7.70 - 8.93 (g/mile)	0.0009 - 0.0014 (g/mile)	0.023 (g/mile)	0.10 - 0.15 (g/mile)	
	2005	B20	HD	Chassis Dyno.	Steady State		6.9 - 11.0 (g/mile)	.1421 (g/mile)	.4599 (g/mile)	1.82 - 4.22 (g/mile)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
	2005	Diesel	HD	Chassis Dyno.	Steady State		6.75 - 11.04 (g/mile)	0.2163 - 0.299 (g/mile)	0.515 - 1.192 (g/mile)	2.13 - 4.98 (g/mile)	
	2000	B20	HD	Chassis Dyno.	Steady State		18.65 (g/mile)	0.23 (g/mile)	.63 (g/mile)	2.63 (g/mile)	
	2000	Diesel	HD	Chassis Dyno.	Steady State		19.80 (g/mile)	0.274 (g/mile)	0.871 (g/mile)	3.60 (g/mile)	
McCormick, R. L.; Williams, A.; Ireland, J.;	2000	B20	HD	Chassis Dyno.	Steady State		18.67 (g/mile)	.22 (g/mile)	.57 (g/mile)	2.73 (g/mile)	
Brimhall, M.; Hayes, R. R. Effects of Biodiesel Blends on Vehicle Emissions;NREL/MP-540-40554; Oct 1,	2000	Diesel	HD	Chassis Dyno.	Steady State		19.44 (g/mile)	0.321 (g/mile)	0.794 (g/mile)	3.43 (g/mile)	
06.	2000	B20	HD	Chassis Dyno.	Steady State		19.04 - 19.7 (g/mile)	.24 (g/mile)	.59266 (g/mile)	2.48 - 2.7 (g/mile)	
	2000	Diesel	HD	Chassis Dyno.	Steady State		19.78 (g/mile)	0.3079 (g/mile)	0.824 (g/mile)	3.04 (g/mile)	
	2000	B20	HD	Chassis Dyno.	Steady State		6.75 - 29.65 (g/mile)	0.0014 - 1.83 (g/mile)	0.023 - 1.192 (g/mile)	0.10 - 27.41 (g/mile)	
	2000	Diesel	HD	Chassis Dyno.	Steady State		20.24 (g/mile)	0.281 (g/mile)	0.824 (g/mile)	3.07 (g/mile)	
	<1991	B20	Various 2-Stroke	On Road	Regular driving conditions		3.2 % change	-1.8 % change	-20.9 % change	-13.9 % change	
	1991	B20	Various 2-Stroke	On Road	Regular driving conditions		3.9 % change	-17.8 % change	-17.5 % change	-12.0 % change	
	<1991	B20	Various 4-Stroke	On Road	Regular driving conditions		2.9 % change	-15.7 % change	-12.2 % change	-13.6 % change	
Morris, R. E.; Pollak, A. K.; Mansell, G. E.; Lindhjem, C.; Jia, Y.; Wilson, G. Impact of Piedlegel Fuels on Air Quality and Livera	1991 - 1993	B20	Various 4-Stroke	On Road	Regular driving conditions		-0.9 % change	-15.7 % change	-2.8 % change	-12.0 % change	
Health;NREL/SR-540-33793; NREL: May, 03.	1994+	B20	Various 4-Stroke	On Road	Regular driving conditions		2.8 % change	-9.8 % change	-17.9 % change	-15.2 % change	
	1991+	B100	Various 2-Stroke	On Road	Regular driving conditions		19.6 % change	-33.0 % change	-72.7 % change	-42.4 % change	
	1991 - 1993	B100	Various 4-Stroke	On Road	Regular driving conditions		13.3 % change	-68.3 % change	-38.7 % change	-41.8 % change	
	1994+	B100	Various 4-Stroke	On Road	Regular driving conditions		9.9 % change	-36.6 % change	-76.3 % change	-41.5 % change	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
	1999	B20 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	EGR and DPF	13.9 (g/mi.)	0.53 (g/mi.)	0.02 (g/mi.)	0.18 (g/mi.)	2461 (g/mi.)
	1999	B50 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	Test Cycle Emission System NOx PM HC CO On Road SAE J1263 EGR and DPF 13.9 (g/mi.) 0.53 (g/mi.) 0.02 (g/mi.) 0.18 (g/mi.) On Road SAE J1263 EGR and DPF 13.1 (g/mi.) 0.34 (g/mi.) 0.02 (g/mi.) 0.13 (g/mi.) On Road SAE J1263 EGR and DPF 11.9 (g/mi.) 0.22 (g/mi.) 0.03 (g/mi.) 0.22 (g/mi.) On Road SAE J1263 EGR and DPF 14.2 (g/mi.) 0.21 (g/mi.) 0.03 (g/mi.) 0.21 (g/mi.) On Road SAE J1263 None 18.0 (g/mi.) 0.30 (g/mi.) 0.03 (g/mi.) 0.19 (g/mi.) On Road SAE J1263 None 16.8 (g/mi.) 0.21 (g/mi.) 0.03 (g/mi.) 0.13 (g/mi.) On Road SAE J1263 None 16.2 (g/mi.) 0.15 (g/mi.) 0.03 (g/mi.) 0.14 (g/mi.) On Road SAE J1263 None 18.7 (g/mi.) 0.14 (g/mi.) 0.03 (g/mi.) 0.14 (g/mi.) On Road SAE J1263 None 18.7 (g/mi.) 0.40 (g/mi.) 0.40 (g/mi.) 0.40 (g/mi.) 0.41 (g/mi.) On Road SAE Speeds None	0.13 (g/mi.)	2452 (g/mi.)			
	1999	B100 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	EGR and DPF	11.9 (g/mi.)	0.22 (g/mi.)	0.03 (g/mi.)	0.22 (g/mi.)	2460 (g/mi.)
Muncrief, R. L.; Rooks, C. W.; Cruz, M.;	1999	B100 Soy Bean Oil	HD	Chassis Dyno.	On Road SAE J1263	EGR and DPF	14.2 (g/mi.)	0.21 (g/mi.)	0.03 (g/mi.)	0.21 (g/mi.)	2464 (g/mi.)
Harold, M. P. Combining biodiesel and exhaust gas recirculation for reduction in NOx and particulate emissions. Energy & Europe 2008, 22 (2), 1285, 1206	1999	B20 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	None	18.0 (g/mi.)	0.30 (g/mi.)	0.03 (g/mi.)	0.19 (g/mi.)	2444 (g/mi.)
Fuels 2000, 22 (2), 1200-1290.	1999	B50 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	None	16.8 (g/mi.)	0.21 (g/mi.)	0.03 (g/mi.)	0.13 (g/mi.)	2382 (g/mi.)
	1999	B100 Cottonseed Oil	HD	Chassis Dyno.	On Road SAE J1263	None	16.2 (g/mi.)	0.15 (g/mi.)	0.03 (g/mi.)	CO 0.18 0.13 0.13 0.13 0.22 (g/mi.) 0.21 (g/mi.) 0.13 0.19 (g/mi.) 0.13 (g/mi.) 0.13 (g/mi.) 0.13 (g/mi.) 0.14 (g/mi.) 0.13 (g/mi.) 0.14 (g/kWh) 8.0 - 14.4 (g/kWh) 8.0 - 13.0 (g/kWh) 8.15.5 (g/kWh) 200 - 415 (ppm) 200 - 410 (ppm) 225 - 565 (ppm)	2443 (g/mi.)
	1999	B100 Soy Bean Oil	HD	Chassis Dyno.	On Road SAE J1263	None	18.7 (g/mi.)	0.14 (g/mi.)	0.03 (g/mi.)	0.13 (g/mi.)	2452 (g/mi.)
	1999	Diesel	HD	Chassis Dyno.	On Road SAE J1263	None	18.7 (g/mi.)	0.40 (g/mi.)			
Murillo. S.: Miquez. J. L.: Porteiro. J.:		B30 Waste Coooking Oil	Outboard Engine	Engine Dyno.	Constant Speeds		5.5 - 13.2 (g/kWh)			8.0 - 14.4 (g/kWh)	
Granada, E.; Moran, J. C. Performance and exhaust emissions in the use of biodiesel in outboard diesel Engines. Fuel 2007, 86 (12-13), 1765-1771.		B100 Waste Coooking Oil	Outboard Engine	Engine Dyno.	Constant Speeds		6.1 - 15.2 (g/kWh)			8.0 - 13.0 (g/kWh)	
		Diesel	Outboard Engine	Engine Dyno.	Constant Speeds		5 - 13.7 (g/kWh)			8 - 15.5 (g/kWh)	
		Palm Kernel Oil	Test Engine	Engine Dyno.	Varying Load		175 - 1125 (ppm)		17 - 39 (ppm)	200 - 415 (ppm)	
Myo, T.; Kinoshita, E.; Tsuru, H.; Hamasaki, K. Combustion Characteristics		Palm Oil	Test Engine	Engine Dyno.	Varying Load		200 - 1100 (ppm)		20 - 45 (ppm)	200 - 400 (ppm)	
Biodiesel and Its Blend (B20). SAE International 2007, JSAE-20076568.		Cottonseed Oil	Test Engine	Engine Dyno.	Varying Load		175 - 1075 (ppm)		18 - 40 (ppm)	200 - 410 (ppm)	
		Diesel	Test Engine	Engine Dyno.	Varying Load		175 - 1200 (pm)		32 - 73 (ppm)	225 - 565 (ppm)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Reference Nagaraju, V.; Henein, N.; Quader, A.; Wu M.; Bryzik, W. Effect of Biodiesel (B-20) on Performance and Emissions in a Single Cylinder HSDI Diesel Engine. SAE International 2008. Okamoto, T.; Nakasato, T.; Konno, M. Fuel Properties and Engine Performance of Dimethyl Ether-Blended Biodiesel Fuels. SAE International 2007, JSAE- 20077080. Ozkan, M. Comparative study of the effect of biodiesel and diesel fuel on a compression ignition Engine's performance, emissions, and its cycle by cycle variations. Energy & Fuels 2007, 21 3627-3636. Patterson, J.; Hassan, M. G.; Clarke, A.; Shama, K.; Hellgardt, K.; Chen, R. Experimental Study of DI Diesel Engine Performance Using Three Different Biodiesel Fuels. New Diesel Engines and Components and CI Engine Performance for Use with Alternative Fuels 2006, SP- 2014 (2006-01-0234).		B20 Soy Bean Oil	Test Engine		Steady State	Turbo, EGR (50%)	50 (ppm)		190 - 220 (ppm)	1480 - 2250 (ppm)	
Nagaraju, V.; Henein, N.; Quader, A.; Wu, M.; Bryzik, W. Effect of Biodiesel (B-20) on Performance and Emissions in a		Diesel	Test Engine		Steady State	Turbo, EGR (50%)	50 (ppm)		220 - 320 (ppm)	1475 - 2500 (ppm)	
Single Cylinder HSDI Diesel Engine. SAE International 2008.		B20 Soy Bean Oil	Test Engine		Steady State	Turbo, EGR (25%)	440 - 450 (ppm)		105 - 150 (ppm)	300 - 700 (ppm)	
		Diesel	Test Engine		Steady State	Turbo, EGR (25%)	440 - 500 (ppm)		110 - 180 (ppm)	275 - 800 (ppm)	
		B100 Palm Oil	Single Cylinder Engine		Constant Speed		325 - 1200 (ppm)				
Okamoto, T.; Nakasato, T.; Konno, M. Fuel Properties and Engine Performance		B50 Palm Oil	Single Cylinder Engine		Constant Speed		325 - 1125 (ppm)				
Fuels. SAE International 2007, JSAE-20077080.		B25 Palm Oil	Single Cylinder Engine		Constant Speed		320 - 1180 (ppm)				
		Diesel	Single Cylinder Engine		Constant Speed		400 - 1100 (ppm)				
Ozkan, M. Comparative study of the effect of biodiesel and diesel fuel on a compression ignition Engine's		B100	LD	Engine Dyno.	Constant Speeds		360 - 650 (ppm)		0.8 - 3.0 (ppm)	.0203 (% vol.)	10.8 - 12.4 (% vol.)
performance, emissions, and its cycle by cycle variations. Energy & Fuels 2007, 21, 3627-3636.		Diesel	LD	Engine Dyno.	Constant Speeds		230 - 575 (% vol.)		0.5 - 2.3 (% vol.)	0.07 - 0.10 (% vol.)	12 - 14 (% vol.)
		B5 Waste Oil	LD	Engine Dyno.	Vary Load and Speed		11 - 22 (g/kWh)				
Patterson, J.; Hassan, M. G.; Clarke, A.;		B100 Waste Oil	LD	Engine Dyno.	Vary Load and Speed		6 - 10 (g/kWh)				
Performance Using Three Different		B5 Soy Bean Oil	LD	Engine Dyno.	Vary Load and Speed		8 - 22 (g/kWh)				
Components and Cl Engine Performance for Use with Alternative Fuels 2006, SP- 2014 (2006 01 0224)		B50 Soy Bean Oil	LD	Engine Dyno.	Vary Load and Speed		6 - 20 (g/kWh)				
2014 (2000-01-0234).		B100 Soy Bean Oil	LD	Engine Dyno.	Vary Load and Speed		4 - 11 (g/kWh)				
		B5 Rapeseed	LD	Engine Dyno.	Vary Load and Speed		9 - 23 (g/kWh)				

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
		B50 Rapeseed	LD	Engine Dyno.	Vary Load and Speed		9 - 22 (g/kWh)				
		B100 Rapeseed	LD	Engine Dyno.	Vary Load and Speed		6 - 10 (g/kWh)				
		Diesel	LD	Engine Dyno.	Vary Load and Speed		8 - 12 (g/kWh)				
		B20 Mahua Oil	Test Engine	Engine Dyno.	Constant Loads		18 - 45 (ppm)			.1123 (% vol.)	
		B40 Mahua Oil	Test Engine	Engine Dyno.	Constant Loads		18 - 50 (ppm)			.0722 (% vol.)	
Raheman, H.; Ghadge, S. V. Performance of compression ignition Engine with		B60 Mahua Oil	Test Engine	Engine Dyno.	Constant Loads		18 - 47 (ppm)			.0612 (% vol.)	
mahua (Madhuca indica) biodiesel. Fuel 2007, 86, 2568-2573		B80 Mahua Oil	Test Engine	Engine Dyno.	Constant Loads		23 - 48 (ppm)			.0508 (% vol.)	
		B100 Mahua Oil	Test Engine	Engine Dyno.	Constant Loads		19 - 47 (ppm)			.0207 (% vol.)	
		Diesel	Test Engine	Engine Dyno.	Constant Loads		17 - 44 (ppm)			.1220 (% vol.)	
Rantanen, L.; Linnaila, R.; Aakko, P.;	1999 - 2004	B5 NExBTL	LD		Steady State	Oxidation Catalyst	24 % change	-35 % change	06 % change	-47 % change from Diesel	-1 - 1 % change
Harju, T. NExBTL - Biodiesel Fuel of the Second Generation. SAE International 2005, 2005-01-3771.	1999 - 2004	B20 NExBTL	LD		Steady State	Oxidation Catalyst	-13 % change	-13 % change	-2030 % change	-2440 % change	-23 % change
	1999 - 2004	B85 NExBTL	LD		Steady State	Oxidation Catalyst	1 - 7 % change	-1830 % change	-4456 % change	-5052 % change	-34 % change
Reksowardojo, I. K.; Brodjonegoro, T. P.; Arismunandar, W.; Sopheak, R.; Ogawa, H. The Combustion and Exhaust Gas		B100 Jatropha	Test Engine	Engine Dyno.	Full Load		100 - 950 (ppm)		580 - 1400 (ppm)	1100 - 8200 (ppm)	
Emission of a Direct Injection Compression Ignition Engine Using Physic Nut Oil (Jatropha Curcas L.oil).		B10 Jatropha	Test Engine	Engine Dyno.	Full Load		200 - 1350 (ppm)		300 - 700 (ppm)	500 - 3800 (ppm)	
SAE International 2007, 2007-01-3622.		Diesel	Test Engine	Engine Dyno.	Full Load		200 - 1450 (ppm)		250 - 575 (ppm)	500 - 3200 (ppm)	
Reksowardojo, I. K.; Lubis, I. H.; Manggala, S. A.; Brodjonegoro, T. P.; Soerawidjaya, T. H.; Arismunandar, W.		B10 Jatropha	Test Engine		ESC		180 - 1400 (ppm)		390 - 950 (ppm)	500 - 2600 (ppm)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
Performance and Exhaust Gas Emissions of Using Biodiesel Fuel from Physic Nut (Jatropha Curcas L.) Oil on a Direct Injection Diesel Engine (DI). SAE International 2007 JSAE 20077278 (SAE		B20 Jatropha	Test Engine		ESC		200 - 1280 (ppm)		420 - 770 (ppm)	400 - 2300 (ppm)	
2007-01-2025), 1232-1236.		B50 Jatropha	Test Engine		ESC		150 - 1280 (ppm)		520 - 850 (ppm)	430 - 1900 (ppm)	
		B100 Jatropha	Test Engine		ESC		180 - 1380 (ppm)		450 - 750 (ppm)	440 - 1800 (ppm)	
		Diesel	Test Engine		ESC		200 - 1250 (ppm)		620 - 1280 (ppm)	480 - 2600 (ppm)	
Saanum, I.; Bysveen, M.; Hustad, J. E. Study of Particulate Matter-,NOx-and Hydrocarbon Emissions from a Diesel Engine Fueled with Diesel Oil and Biodiesel with Fumigation of Hydrogen, Methane and Propane. SAE International 2008, 2008-01-1809.	1995	B80 Rapeseed	MD		Varying Load	EURO 2	10 - 13.5 (g/kWh)	.0412 (g/kWh)	0.3 - 5.5 (g/kWh)		
2008, 2008-01-1809.		B20 Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		25 - 88 (ppm)		1.3 - 3.4 (ppm)		.46 (% vol.)
		B40 Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		28 - 78 (ppm)		1.2 - 2.8 (ppm)		.56 (% vol.)
Sahoo, P. K.; Das, L. M.; Babu, M. K. G.; Naik, S. N. Biodiesel development from		B60 Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		28 - 80 (ppm)		1.2 - 2.2 (ppm)		.56 (% vol.)
performance evaluation in a CI Engine. Fuel 2007, 86 (3), 448-454.		B80 Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		25 - 78 (ppm)		0 - 2.6 (ppm)		.46 (% vol.)
		B100 Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		27 - 76 (ppm)		.4 - 1.2 (ppm)		.46 (% vol.)
		Diesel Polanga Oil	LD	AC Generator/ Load bank	Constant Loads		28 - 75 (ppm)		1.3 - 3.0 (ppm)		.46 (% vol.)
Savvidis, D.; Triandafyllis, J.; Grammatikis, V.; Gkatzianis, G.;	1986	B10 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	320 - 370 (ppm)				10.5 (% vol.)
Pecqueur, M. A New Volvo V/0 2.5 and an Old Ford Escort 1.6 Were Tested and Compared on a Chassis Dynamometer, Using the Same Blends of Frving	1986	B20 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	300 - 380 (ppm)				10.4 - 11 (% vol.)
Biodiesel and Neat Diesel. SAE International 2008, 2008-01-1576.	1986	B30 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	305 - 400 (ppm)				10.1 - 10.5 (% vol.)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
	1986	B40 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	300 - 380 (ppm)				10.1 - 10.5 (% vol.)
	1986	B50 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	300 - 390 (ppm)				9.9 - 10.7 (% vol.)
	1986	B100 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	310 - 400 (ppm)				10.2 - 10.6 (% vol.)
	2003	B10 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	530 - 790 (ppm)				11.5 - 11.7 (% vol.)
	2003	B20 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	590 - 800 (ppm)				11.4 - 11.6 (% vol.)
	2003	B30 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	615 - 810 (ppm)				11.4 - 11.6 (% vol.)
	2003	B40 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	640 - 820 (ppm)				11.4 - 11.5 (% vol.)
	2003	B50 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	680 - 820 (ppm)				11.5 - 11.6 (% vol.)
Savvidis, D.; Triandafyllis, J.; Grammatikis, V.; Gkatzianis, G.;	2003	B100 Frying Oil	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	690 - 850 (ppm)				11.5 - 11.6 (% vol.)
Pecqueur, M. A New Volvo V70 2.5 and an Old Ford Escort 1.6 Were Tested and Compared on a Chassis Dynamometer, Using the Same Blends of Erving	2003	Diesel	LD	Chassis Dyno.	Constant Speeds, Difft Gears	ECU, EGR	500 - 660 (ppm)				11.8 - 12 (% vol.)
Biodiesel and Neat Diesel. SAE International 2008, 2008-01-1576.	1986	Diesel	LD	Chassis Dyno.	Constant Speeds, Difft Gears	No ECU, EURO 1	300 - 360 (ppm)				10.7 - 11.2 (% vol.)
Sharp, C. A.; Ryan, T. W.; Knothe, G. Heavy-Duty Diesel Engine Emissions	2003	B100 Soy bean oil	HD		CFR title 40 part 86 subpart N	turbo, EGR	2.54 - 2.56 (g/hp-hr)	0.024 - 0.026 (g/hp-hr)	0.02 - 0.06 (g/hp-hr)	0.40 (g/hp-hr)	
Tests using Special Biodiesel Fuels. SAE International 2005.	2003	Diesel	HD		CFR title 40 part 86 subpart N	turbo, EGR	2.20 - 2.26 (g/hp-hr)	0.102 - 0.1.4 (g/hp-hr)	0.05 - 0.07 (g/hp-hr)	0.51 - 0.53 (g/hp-hr)	
Sheehan, J.; Camobreco, V.; Duffield. J.;		B20 Soybean Oil	HD	On Road	Steady State		4.9 (g/bhp-h)	.07 (g/bhp-h)	.09 (g/bhp-h)	1.1(g/bhp- h)	520 (g/bhp-h)
Graboski, M.; Shapouri, H. An Overview of Biodiesel and Petroleum Diesel Life Cycles;NREL/TP-580-24772; NREL: May, 08		B100 Soybean Oil	HD	On Road	Steady State		5.2 (g/bhp-h)	.03 (g/bhp-h)	.06 (g/bhp-h)	543 (g/bhp-h)	130 (g/bhp-h)
		Diesel	HD	On Road	Steady State		4.8 (g/bhp-h)	0.08 (g/bhp-h)	0.1 (g/bhp-h)	1.2 (g/bhp-h)	633 (g/bhp-h)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
		B20 Rice Bran	MD	Engine Dyno.	Constant speeds and loads (IS 14599:1999		3.1 - 4.3 (g/kWh)		0.24 - 0.4 (g/kWh)	2.8 - 5.1 (g/kWh)	10.7 - 11.9 (%)
Sinha, S.; Agarwai, A. K. Ricebran Oil Biodiesel's Performance, Emission and Endurance Test on a CIDI Transport Engine. SAE International 2008.		B50 Rice Bran	MD	Engine Dyno.	Constant speeds and loads (IS 14599:1999		3.4 - 4.7 (g/kWh)		0.2 - 0.31 (g/kWh)	2.0 - 3.0 (g/kWh)	10.2 - 11.5 (%)
		Diesel	MD	Engine Dyno.	Constant speeds and loads (IS 14599:1999		3.0- 4.1 (g/kWh)		0.33 - 0.52 (g/kWh)	3.7 - 5.3 (g/kWh)	11.5 - 12.7 (%)
		B50 Rice Bran Oil	LD	Engine Dyno.	Constant speeds and loads		4.7 - 5.3 (g/kWh)		0.4 - 1.0 (g/kWh)	3.0 - 5.0 (g/kWh)	
Sinha, S.; Agarwal, A. K. Performance Evaluation of a Biodiesel (Rice Bran Oil Mathul Ector) Evaluat Transport Discol		B30 Rice Bran Oil	LD	Engine Dyno.	Constant speeds and loads		4.2 - 5.1 (g/kWh)		0.5 - 0.8 (g/kWh)	2.8 - 6.1 (g/kWh)	
Engine. SAE Technical Paper Series 2005.		B10 Rice Bran Oil	LD	Engine Dyno.	Constant speeds and loads		4.5 - 6.6 (g/kWh)		1.3 - 4.6 (g/kWh)	4.0 - 8.0 (g/kWh)	
		Diesel	LD	Engine Dyno.	Constant speeds and loads		3.0 - 4.2 (g/kWh)		0.5 - 1.4 (g/kWh)	5.0 - 9.5 (g/kWh)	
		B100 Rice Bran Oil	LD	Engine Dyno.	Constant Loads		6.82 (g/kWh)		0.26 (g/kWh)	1.7 (g/kWh)	
Sinha, S.; Agarwal, A. K.; Garg, S. Biodiesel development from rice bran oil: Transesterification process optimization		B50 Rice Bran Oil	LD	Engine Dyno.	Constant Loads		6.80 (g/kWh)		0.3 (g/kWh)	2.0 (g/kWh)	
and fuel characterization. Energy Conversion and Management 2008, 49 (5), 1248-1257.		B20 Rice Bran Oil	LD	Engine Dyno.	Constant Loads		6.60 (g/kWh)		0.49 (g/kWh)	2.3 (g/kWh)	
		Diesel	LD	Engine Dyno.	Constant Loads		6.15 (g/kWh)		0.65 (g/kWh)	2.9 (g/kWh)	
		B100 Jatropha	LD	Engine Dyno.	Various Brake Power		445 - 515 (ppm)				
Sivaprakasam, S.; Saravanan, C. G. Optimization of the transesterification process for biodiesel production and use		B60 Jatropha	LD	Engine Dyno.	Various Brake Power		175 - 500 (ppm)				
of biodiesel in a compression ignition Engine. Energy & Fuels 2007, 21, 2998- 3003.		B20 Jatropha	LD	Engine Dyno.	Various Brake Power		150 - 460 (ppm)				
		Diesel	LD	Engine Dyno.	Various Brake Power		120 - 530 (ppm)				
Srivastava, P. K.; Verma, M. Methyl ester of karanja oil as an alternative renewable		B20 Karanja Oil	LD	Engine Dyno.	Constant Speed		175 - 600 (ppm)		40 - 105 (ppm)	0.10 - 0.20 (%)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO2
source energy. Fuel 2008, 87 (8-9), 1673- 1677.		B70 Karanja Oil	LD	Engine Dyno.	Constant Speed				48 - 135 (ppm)	0.13 - 0.20 (%)	
		B100 Karanja Oil	LD	Engine Dyno.	Constant Speed		190 - 680 (ppm)		32 - 90 (ppm)	0.075 - 0.15 (%)	
		Diesel	LD	Engine Dyno.	Constant Speed		125 - 590 (ppm)		25 - 80 (ppm)	0.07 - 0.11 (%)	
Suh, H. K.; Roh, H. G.; Lee, C. S. spray and combustion characteristics of biodiesel/diesel blended fuel in a direct		B20 Soy	LD	Engine Dyno.	Constant Speed		25 - 375 (ppm)		50 - 80 (ppm)	.0555 (%)	
injection common-rail diesel Engine. Journal of Engineering for Gas Turbines and Power-Transactions of the Asme 2008, 130 (3).		Diesel	LD	Engine Dyno.	Constant Speed		25 - 250 (ppm)		75 - 150 (ppm)	0.05 - 0.18 (%)	
		B100 Jatropha	Test Engine	Engine Dyno.	Constant Speed, varying injection timing		680 - 890 (ppm)		72 - 84 (ppm)	0.28 - 0.30 (%)	
Sundarapandian; Devaradjane Theoretical and Experimental Investigation of the Performance of Venetable Oil Operated		B100 Mahua Oil	Test Engine	Engine Dyno.	Constant Speed with varying injection timing		650 - 880 (ppm)		76 - 86 (ppm)	0.27 - .031 (%)	
CI Engine. SAE International 2007, JSAE- 20076567.		B100 Neem Oil	Test Engine	Engine Dyno.	Constant Speed with varying injection timing		660 - 875 (ppm)		78 - 86 (ppm)	0.28 - 0.31 (%)	
		Diesel	Test Engine	Engine Dyno.	Constant Speed with varying injection timing		700 - 910 (ppm)		90 - 110 (ppm)	0.34 - 0.37 (%)	
		B20 Pongamia	Test Engine	Generator w/ rheostat	Constant Speed with varying load		85 - 220 (ppm)		1 (ppm)	.0103 (% vol.)	1.9 - 3.0 (% vol.)
		B40 Pongamia	Test Engine	Generator w/ rheostat	Constant Speed with varying load		50 - 160 (ppm)			0.02 (% vol.)	.9 - 1.5 (% vol.)
Sureshkumar, K.; Velraj, R.; Ganesan, R. Performance and exhaust emission characteristics of a CI Engine fueled with		B60 Pongamia	Test Engine	Generator w/ rheostat	Constant Speed with varying load		48 - 150 (ppm)				0.5 - 0.7 (% vol.)
Pongamia pinnata methyl ester (PPME) and its blends with diesel. Renewable Energy 2008, 33 (10), 2294-2302.		B80 Pongamia	Test Engine	Generator w/ rheostat	Constant Speed with varying load		50 - 165 (ppm)			.00601 (% vol.)	1.6 - 2.7 (% vol.)
		B100 Pongamia	Test Engine	Generator w/ rheostat	Constant Speed with varying load		75 - 190 (ppm)			.00701 (% vol.)	1.6 - 2.5 (% vol.)
		Diesel	Test Engine	Generator w/ rheostat	Constant Speed with varying load		75 - 240 (ppm)		1 - 2 (ppm)	0.02 (% vol.)	0.5 - 2.7 (% vol.)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO2
		B20 Pongamia	Test Engine	Engine Dyno.	Various loads	EGR	75 - 1500 (ppm)		26 - 43 (ppm)		
		B40 Pongamia	Test Engine	Engine Dyno.	Various loads	EGR	100 - 1600 (ppm)		22 - 43 (ppm)		
Suryawanshi, J. G.; Deshpande, N. V. Overview of EGR, Injection Timing and		B60 Pongamia	Test Engine	Engine Dyno.	Various loads	EGR	75 - 1500 (ppm)		20 - 43 (ppm)		
of CI Engine with Pongaia Methyl Ester. SAE Technical Paper Series 2005.		B80 Pongamia	Test Engine	Engine Dyno.	Various loads	EGR	150 - 1450 (ppm)		16 - 43 (ppm)		
		B100 Pongamia	Test Engine	Engine Dyno.	Various loads	EGR	100 - 1500 (ppm)		13 - 44 (ppm)		
		Diesel	Test Engine	Engine Dyno.	Various loads	EGR	200 - 1400 (ppm)		33 - 43 (ppm)		
Suryawanshi, J. G.; Deshpande, N. V. The Effects of Combination of EGR.		B20 Jatropha	Test Engine	Engine Dyno.	Constant Speed	EGR	100 - 1350 (ppm)		25 - 42 (ppm)		
Suryawanshi, J. G.; Deshpande, N. V. The Effects of Combination of EGR, Injection Retard and Injection Pressure on	B20 Jatropha Test Engine Engine Dyno. Consist Spectrum V. V. R, ssure on esel B40 Jatropha Test Engine Engine Dyno. Consist Spectrum B40 Jatropha Test Engine Engine Dyno. Consist Spectrum B40 Jatropha Test Engine Engine Dyno. Consist Spectrum B40 Jatropha Test Engine Engine Dyno. Spectrum	Constant Speed	EGR	100 - 1350 (ppm)		20 - 45 (ppm)					
Emissions and Performance of Diesel Engine Fuelled With Jatropha Oil Methyl Ester, ASME International Mechanical		B80 Jatropha	Test Engine	Engine Dyno.	Constant Speed	EGR	150 - 1350 (ppm)		17 - 27 (ppm)		
Engineering Congress and Exposition 2006, IMECE2006-13021, 1-12.		B100 Jatropha	Test Engine	Engine Dyno.	Constant Speed	EGR	175 - 1350 (ppm)		17 - 28 (ppm)		
		Diesel	Test Engine	Engine Dyno.	Constant Speed	EGR	225 - 1500 (ppm)		33 - 44 (ppm)		
	2006	B20 Soy Bean Oil	HD	Engine Dyno.	FTP,UDDS (28k), UDDS (6k), HWY, HWY (172), NRTC,WHTC	EGR	2.5 - 6.1 (g/bhphr)	.035063 (g/bhphr)	.0317 (g/bhphr)	0.48 - 1.70 (g/bhphr)	590 - 690 (g/bhphr)
Sze, C.; Whinihan, J. K.; Olson, B. A.; Schenk, C. R.; Sobotowski, R. A. Impact of Test Cycle and Biodiesel Concentration on Emissions. SAE 2007 Transactions Journal of Fuels and Lubricants 2007, V116-4 (2007-01-4040).	2006	B50 Soy Bean Oil	HD	Engine Dyno.	FTP,UDDS (28k), UDDS (6k), HWY, HWY (172), NRTC,WHTC	EGR	2.8 - 6.2 (g/bhphr)	.02203 (g/bhphr)	.02513 (g/bhphr)	.37 - 1.50 (g/bhphr)	585 - 680 (g/bhphr)
	2006	Diesel	HD	Engine Dyno.	FTP,UDDS (28k), UDDS (6k), HWY, HWY (172), NRTC,WHTC	EGR	2.3 - 6.0 (g/bhphr)	0.06 - 0.09 (g/bhphr)	0.04 - 0.19 (g/bhphr)	0.6 - 1.8 (g/bhphr)	545 - 690 (g/bhphr)

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	нс	со	CO ₂
		B20 Soy Bean Oil	Test Engine		Constant Speed		7 - 15 (g/kWh)				
Szybist, J. P.; Kirby, S. R.; Boehman, A. L. NOx emissions of alternative diesel		B40 Soy Bean Oil	Test Engine		Constant Speed		8 - 17 (g/kWh)				
and FT diesel. Energy & Fuels 2005, 19 (4), 1484-1492.		B100 Soy Bean Oil	Test Engine		Constant Speed		7 - 17 (g/kWh)				
		Diesel	Test Engine		Constant Speed		8 - 17.5 (g/kWh)				
Tsolakis, A. Effects on particle size distribution from the diesel Engine		B100 Rapeseed Oil	Test Engine	Engine Dyno.	3 Different Engine Operating Conditions	EGR	580 - 920 (ppm)				
operating on RME-biodiesel with EGR. Energy & Fuels 2006, 20 (4), 1418-1424.		Diesel	Test Engine	Engine Dyno.	3 Different Engine Operating Conditions	EGR	200 - 700 (ppm)				
Verhaeven, E.; Pelkmans, L.; Govaerts, L.; Lamers, R.; Theunissen, F. Results of demonstration and evaluation projects of biodiesel from rapeseed and used frying oil on light and heavy duty vehicles. SAE International 2005.		B100 Used Vegetable Oil	LD	On Road	Traffic conditions	Oxidation Catalyst	27 - 31 (g/km)		1.4 - 2.0 (g/km)	7.8 - 8.7 (g/km)	
Wang, W. G.; Lyons, D. W.; Clark, N. N.; Gautam, M.; Norton, P. M. Emissions from nine heavy trucks fueled by diesel and biodiesel blend without Engine modification. Environmental Science & Technology 34[6], 933-939. 2000.		B35 Soybean Oil	HD	Chassis Dyno.	Truck Cylce/Mile Route Cycle		20 - 260 (ppm)	0.2 - 2.1 (g/mi.)	9 - 13 (ppm)	10 - 210 (ppm)	
Williams, A.; McCormick, R. L.; Hayes, R. R.; Ireland, J.; Fang, H. L. Effect of	2002	B20 Soy Bean Oil	HD	Engine Dyno.	Steady State	EGR, DPF	2.22 - 2.27 (g/bhp-hr)	0.0009 - 0.0012 (g/bhp-hr)	-0.001 - 0.001 (g/bhp-hr)	0.01 - 0.05 (g/bhp-hr)	
Biodiesel Blends on Diesel Particulate Filter Performance. SAE: 2006.	2002	Diesel	HD	Engine Dyno.	Steady State	EGR, DPF	2.14 - 2.20 (g/bhp-hr)	.0010 - 0.0017 (g/bhp-hr)	0.001 - 0.004 (g/bhp-hr)	0.02 - 0.06 (g/bhp-hr)	
Williams A · McCormick R L · Haves R ·	2002	B20 Soybean Oil	HD	Engine Dyno.	Steady State	EGR/ Diesel Oxidation Catalyst (CCRT)	2.15 - 2.18 (g/bhp-hr)	.001002 (g/bhp-hr)	0.001 (g/bhp-hr)	0.01 (g/bhp-hr)	
Particle Filter Performance;NREL/TP-540- 39606; Mar, 06.	2002	B20 Soybean Oil	HD	Engine Dyno.	Steady State	EGR	2.13 - 2.23 (g/bhp-hr)	.061074 (g/bhp-hr)	.1317 (g/bhp-hr)	.99 - 1.14 (g/bhp-hr)	
	2002	Diesel	HD	Engine Dyno.	Steady State	EGR	2.05 (g/bhp- hr)	0.0859 (g/bhp-hr)	0.172 (g/bhp-hr)	1.19 (g/bhp-hr)	

Reference	Model Year	Fuel	Engine	Test	Test Cycle	Emission Control System	NOx	РМ	НС	со	CO ₂
Wu, Y. P. G.; Lin, Y. F.; Chang, C. T. Combustion characteristics of fatty acid		B100 Waste cooking oil	LD		Constant Speed		5 - 160 (ppm)	80 - 460 (mg/m ³)	10 - 50 (ppm)	.02524 (% vol.)	2.5 - 4.0 (% vol.)
methyl esters derived from recycled cooking oil. Fuel 2007, 86, 2810-2816.		Diesel	LD		Constant Speed		5 - 25 (ppm)	15 - 100 (mg/m³)	10 - 20 (ppm)	.0309 (% vol.)	2.6 - 3.0 (% vol.)
Zervas, E. Regulated and non-regulated pollutants emitted from two aliphatic and a commercial diesel fuel. Fuel 2008, 87 (7), 1141-1147.		B100	LD		New European Driving Cycle	Diesel Oxidation Catalyst	.3842 (g/km)	.0304 (g/km)	.1025 (g/km)	.0832 (g/km)	
		B10 Waste Cooking Oil	LD	Chassis Dyno.	Constant Speeds with varying loads	EGR and Diesel Oxidation Catalyst	180 - 780 (x10 ⁻⁶)			2.3 - 9.2 (x10⁻⁶)	.038078
Zhang, X.; Wang, H.; Li, L.; Wu, Z.; Hu,		B20 Waste Coooking Oil	LD	Chassis Dyno.	Constant Speeds with varying loads	EGR and Diesel Oxidation Catalyst	180 - 775 (x10 ⁻⁶)			2.3 - 8.2 (x10⁻⁶)	.038078
Z.; Zhao, H.; Yang, W. Characteristics of Particulates and Exhaust Gases Emissions of DI Diesel Engine Employing Common Rail Fuel System Fueled with Bio-diesel Blends. SAE International		B40 Waste Cooking Oil	LD	Chassis Dyno.	Constant Speeds with varying loads	EGR and Diesel Oxidation Catalyst	180 - 800 (x10 ⁻⁶)			2.0 - 5.0 (x10 ⁻⁶)	.038078
2008, 2008-01-1834.		B60 Waste Cooking Oil	LD	Chassis Dyno.	Constant Speeds with varying loads	EGR and Diesel Oxidation Catalyst	180 - 810 (x10 ⁻⁶)			1.9 - 4.2 (x10 ⁻⁶)	.038078
		B100 Waste Cooking Oil	LD	Chassis Dyno.	Constant Speeds with varying loads	EGR and Diesel Oxidation Catalyst	180 - 1050 (x10 ⁻⁶)			1.8 - 3.2 (x10 ⁻⁶)	.038081
Zhang, Y.; Boehman, A. L. Impact of biodiesel on NOx emissions in a common		B20	LD		Low load and High load	EGR	2.8 - 5.8 (g/kWh)				
rail direct injection diesel Engine. Energy & Fuels 2007, 21 (4), 2003-2012.		B40	LD		Low load and High load	EGR	2.7 - 6.4 (g/kWh)				
		B100 Soy Bean Oil	Test Engine	Engine Dyno.	Steady Shot	EGR	8.0 (g/kWh)		0.1 (g/kWh)	2.3 (g/kWh)	
Zheng, M.; Mulenga, M. C.; Reader, G. T.; Wang, M. P.; Ting, D. S. K.; Tjong, J.		B100 Canola	Test Engine	Engine Dyno.	Steady Shot	EGR	3.3 (g/kWh)		0.2 (g/kWh)	3.0 (g/kWh)	
emissions in low temperature combustion. Fuel 2008, 87 (6), 714-722.		B100 Yellow Grease	Test Engine	Engine Dyno.	Steady Shot	EGR	3.8 (g/kWh)		0.2 (g/kWh)	2.2 (g/kWh)	
		Diesel	Test Engine	Engine Dyno.	Steady Shot	EGR	3.7 (g/kWh)		0.4 (g/kWh)	4.25 (g/kWh)	

Appendix V-2. Aldehyde Emissions from Biodistillates

Reference	Fuel Engine Test Test Cycle		Emission Control	Formaldehyde	Acetaldehyde		
Ballesteros, R.; Hernandez, J. J.; Lyons, L. L.; Cabanas, B.; Tapia, A. Speciation of the semivolatile hydrocarbon engine emissions from sunflower biodiesel. Fuel 2008, 87 (10-11), 1835-1843.	B100	LD	Chassis	European Emission Directive 70/220 (Extra Urban and Urban mode)	turbo, EGR	0 - 0.23 (mg/kWhr)	
Graboski, M. S.; McCormick, R. L.	B20	HD	Chassis	Steady State		0.31 - 0.48 (g/mile)	
derived fuels in diesel engines. Progress	B20	HD	Chassis	Steady State	catalyst	0.25 - 0.34 (g/mile)	
24 (2), 125-164.	Diesel	HD	Chassis	Steady State		0.31 - 0.4 (g/mile)	
McCormick, R. L. The Impact of Biodiesel	B20	HD		Heavy-Duty Transient		26 - 70 (mg/bhp-h)	
on Pollutant Emissions and Public Health. Inhalation Toxicology 2006, 19 (1033-	B100	HD		Heavy-Duty Transient		20 - 55 (mg/bhp-h)	
1039), 1033-1039.	Diesel	HD		Heavy-Duty Transient		30 - 100 (mg/bhp-h)	
Pang, X. B.; Mu, Y. J.; Yuan, J.; He, H. Carbonyls emission from ethanol-blended	Dlesel	HD		varying speeds		60 - 108 (mg/kWhr)	55 - 110 (mg/kWhr)
used in engines. Atmos. Environ. 2008, 42 (6), 1349-1358.	BE20 (5% ethanol)	HD		varying speeds		45 - 108 (mg/kWhr)	70 - 120 (mg/kWhr)
Peng, C. Y.; Yang, H. H.; Lan, C. H.; Chien, S. M. Effects of the biodiesel blend fuel on aldebyde emissions from diasel	B20	LD	Engine Dyno.	US Transient cycle		8 - 11.5 (mgbhp/h)	4.4 - 12.2 (mgbhp/h)
engine exhaust. Atmos. Environ. 2008, 42 (5), 906-915.	Diesel	LD	Engine Dyno.	US Transient cycle		11.5 - 15.2 (mgbhp/h)	5.6 - 7.7 (mgbhp/h)
Rantanen. L.: Linnaila. R.: Aakko. P.:	B5 NExBTL	LD		Steady State	Oxidation Catalyst	-4 %	-67 %
Harju, T. NExBTL - Biodiesel Fuel of the Second Generation. SAE International	B20 NExBTL	LD		Steady State	Oxidation Catalyst	-3820 %	-5220 %
2005, 2005-01-3771.	B85 NExBTL	LD		Steady State	Oxidation Catalyst	-42 %	-41 %
U.S.EPA A comprehensive analysis of biodiesel impacts on exhaust	B20	HD				-7.8 %	-7.1 %
emissions;EPA420-P-02-001; U.S. Environmental Protection Agency: Ann Arbor, MI, 02.	B100	HD				-15.1 %	-14.4 %
Zervas, E. Regulated and non-regulated pollutants emitted from two aliphatic and a	Diesel	LD		Steady State	Oxidation Catalyst	8.7 (mg/km)	4 (mg/km)
commercial diesel fuel. Fuel 2008, 87 (7), 1141-1147.	B100	LD		Steady State	Oxidation Catalyst	0.8 - 2.5 (mg/km)	0.5 - 1.2 (mg/km)

Appendix VI. Life-Cycle Assessment (LCA) of Biodistillates

Appendix VI -1 Biodistillate Life-Cycle Assessment (LCA) Literature Appendix VI-2 Biodistillate Life-Cycle Assessment (LCA) Results

Appendix VI-1. Biodistillate Life-Cycle Assessment (LCA) Literature

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Study No	Ref. No	Reference	Year	Qutline/Objective	Results
13	(334)	Gartner, S.O., Helms, H., Reinhardt, G., Rettenmaier, N.; An Assessment of Energy and Greenhouse Gases of NExBTL. IFEU Final Report 530-025	2006	Energy and GHG of production of NExBTL (through hydro-treating) compared to conventional diesel for different conditions at an existing plant in Porvoo, Finland.	NExBTL has an advantage over conventional diesel in terms of energy and GHG for options and scenarios studied. Results mainly depend on feedstocks and alternative uses of land. LHV of NExBTL =44MJ/kg
14	(336)	Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D.; Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS vol. 103, no. 30	2006	LCA determination of biodiesel from soybean and corn ethanol in the US.	Biodiesel provides energy and GWP advantages over both diesel and ethanol.
15	(325)	Niederl, A., Narodoslawsky, M.; Ecological Evaluation of Processes Based on By-Products or Waste from Agriculture: Life Cycle Assessment of Biodiesel from Tallow and Used Vegetable Oil. Chapter 18 in Feedstocks for the Future, American Chemical Society	2006	Biodiesel from genuine waste material (used vegetable oil). Three different scenarios based on the origin of the UVO.	Biodiesel from tallow and UVO have GWP benefit. Also have lower environmental impacts (EUP,ACP, POCP, ABD) than biodiesel that is not produced from waste (RME for example).
16	(332)	Cocco, D.; Comparative study on energy sustainability of biofuel production chains. Proceedings of the Institution of Mechanical Engineers, Part A: J. Power and Energy. Vol. 221. 637-645	2007	Comparative analysis of three most promising bio- energy: power from lignocellulose; biodiesel from oil crops; and, bioethanol from sugar crops.	Study included bioethanol and electricity. Only press cake and glycerin were considered as by-products. Straw can also be used for feedstock in thermoelectric plants. Biodiesel energy investment can be increased if cultivation residues (straw) can be considered a by-product used for power generation. Allocation to co-products increases output/input energy ratios.
17	(407)	Cunningham, J.; Analysis of lifecycle of biodiesel from farmer's field to pump reveals a startling reduction in overall carbon emissions compared to regular fuel Professional Engineering Article. June 13, 2007	2007	Short article describing LCA research by Northeast Biofuels.	Biodiesel LCA results completed show a 94% reduction in CO ₂ equivalent emissions.
18 •	(307)	Edwards, R., Larive, J-F., Mahieru, V., Rouveirolles, P.; WTW Analysis of future automotive fuels and power trains in the European context: WTT Report (Version 2c 2007). EUCAR, CONCAWE JRC, Version c, 2007	2007	Large study on many pathways to alternative fuels. Parts of study include WTT, TTW and WTW. Biodiesel study includes comparison of RME, REE and SME. Also incl. syn-diesel and DME from NG, Coal and Wood.	Biodiesel study: Using grazing or forest land for planting in short or medium term would be counter-productive. Advanced biofuels have potential of substituting fossil fuels, but with potentially higher energy and economical costs. Biofuel GHG savings are dependent on manufacturing process. 2nd generation biofuel production such as BTL have substantially higher GHG savings than traditional biofuels, but with high energy costs. DME has the best GHG savings and lowest energy costs compared to other GTL or BTL fuels.
19	(313)	EPA; Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use. EPA420-F-07- 035	2007	Brief brochure on the importance of full fuel LCA. Comparison between different alternative fuel types.	A brief discussion of comparison between a variety of fuels. The best choice: Cellulosic ethanol reduces CO ₂ emissions by 91%.
20	(408)	Fleming. J.S., Stanciulescu, V., Reilly-Roe, P.; Policy considerations derived from transportation fuel life cycle assessment. SAE 2007-01-1606	2007	23 fuel-vehicle pathways were considered to test viability of each and make policy recommendations; 4 are for biodiesel specifically.	Next generation pathways have high GHG emissions reduction potential.
21	(326)	Guinee, J.B., Heijungs, R.; Calculating the Influence of Alternative Allocation Scenarios in Fossil Fuel Chains. Int. J. LCA 12, (3) 173-180	2007	A quick scan LCA to elaborate on different allocation scenarios (economic, physical and ecoinvent default) for multi-output processes for average Dutch passenger car.	A scan of other LCA models shows that different allocation methods of co-products generate large differences in LCA results.
22	(330)	Hansson, P-A., Baky, A., Ahlgren, S., Bernesson, S., Nordberg, A., Noren, O., Pettersson, O.; Self-sufficiency of motor fuels on organic farmsEvaluation of systems based on fuels produced in industrial scale plants. Agricultural Systems 94, (2007) 704-714	2007	LCA of RME, ethanol and biogas produced from processing raw material from an organic farm in industrial scale plants for use on the farm to make it self sufficient.	RME showed best energy efficiency and favorable GWP. The technology for conversion is well known, and no engine modifications were necessary. However, the cost is higher than fossil diesel.
23	(342)	Harding, K.G., Dennis, J.S., von Blottnitz, H., Harrison, S.T.L.; A life-cycle comparison between inorganic and biological catalysis for the production of biodiesel. Journal of Cleaner Production 16, (2007) 1368-1378	2007	5 cases of 1000kg biodiesel production from different catalyst types (NaOH or biological enzyme Candida antarctica), use of ethanol or methanol, and efficiency of alcohol recovery.	LCA results in lower GHG benefit for alkali catalyzed process w/ low alcohol recovery. Ethanol instead of methanol gives mixed results.

Study No.	Ref. No.	Reference	Year	Outline/Objective	Results
24	(178)	Kalnes, T., Marker, T., Shonnard, D.; Green Diesel: A Second Generation Biofuel. Int. J Chemical Reactor Engineering 5. A48	2007	LCA of Ecofining (hydro-treating) soy oil. Two scenarios for different H ₂ production.	Green diesel compares favorably to biodiesel and fossil energy. Fossil energy consumption is reduced by 84-90% when H_2 is produced from byproducts.
25	(181)	Kaufman, J.; Renewable Diesel. Presentation, SAE Govt/ Industry Meeting May 15, 2007	2007	Presentation of results of LCA study of renewable diesel from soybean oil compared to Biodiesel and Petroleum diesel	LCA results are presented on a relative basis. Renewable Diesel is a good way to incorporate fats and oils into diesel fuels.
26	(327)	Kreider, J.F., Curtiss, P.S.; Comprehensive Evaluation of Impacts from Potential, Future Automotive Replacement Fuels. Proceedings of ES2007; ES2007- 36264	2007	Study investigating potential future fuels and their sources to determine the most sustainable direction for US transportation fuels.	Biodiesel yields are smallest per acre of any land based fuel; water demands are high. Soybean based biodiesel has a low potential to reduce oil imports.
27	(176)	Kuronen, M., Mikkonen, S.; Hydro treated Vegetable Oil as Fuel for Heavy Duty Diesel Engines. SAE 2007-01- 4031	2007	Summary of emissions testing on NExBTL 2nd generation biodiesel fuel.	Results of an LCA discussed showed that NExBTL reduces emissions by 40-60% compared to fossil diesel.
28	(329)	Prueksakorn, K., Gheewala, S.H.; Full Chain Energy Analysis of Biodiesel from Jatropha curcas L. in Thailand. Environmental Science Technology, 42, 3388- 3393	2007	Investigated the energy consumption for 20-year investment of Jatropha Methyl Ester production in Thailand.	Study includes a wide range of sensitivity to efficiencies and yields. Overall, results show a net energy benefit for using jatropha as a feedstock for biodiesel, and will support policy decisions.
29	(409)	Reinhardt, G., Rettenmaier, N., Gartner, S., Pastowski, A.; Rain Forest for Biodiesel? Ecological effects of using palm oil as a source of energy. WWF Germany	2007	Non-RE and GHG of palm oil cultivation, including various LUC. Comparison to conventional diesel and biodiesel for use in vehicles or power stations.	Energy balance is positive for palm oil compared to other biofuels. However, only cultivation of fallow land has a positive effect on GHG.
30	(341)	Ahlgren, S., Baky, A., Bernesson, S., Nordber, A., Noren, O., Hansson, P.A.; Future fuel supply systems for organic production based on Fischer-Tropsch diesel and dimethyl ether from on-farm grown biomass. Biosystems Engineering 99, 145-155	2008	Conducted 4-scenarios of either Fischer-Tropsch diesel (FTD) or Dimethyl ether (DME) from two different organically grown feedstocks.	FTD is more likely alternative, although it requires more land to be set aside, it produces more useful co-products. It produces 12% more GWP than DME but has lower cost. Compared to diesel, all scenarios showed reduced environmental impact. NOTE: "functional unit" not defined well. Requirement for 1000 ha of land, same as in Hansson, 2007.
31	(318)	Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W.; N ₂ O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics, 8. 389-395	2008	IPCC estimate of N ₂ O conversion from N is too low, resulting in LCA models underestimating global impacts	N_2O emissions estimates from current modeling techniques need to be reexamined, may underestimate N_2O emissions, which have 246 times the impact of CO_2 .
32	(410)	Halleux, H., Lassaux, S., Renzoni, R., Germain, A.; Comparative Life Cycle Assessment of Two Biofuels: Ethanol from Sugar Beet and Rapeseed Methyl Ester. International Journal of Life Cycle Assessments, (3) 184-190	2008	Comparison of biofuels to fossil diesel with a base- case scenario and different sensitivity analyses for allocation method and N_2O emission. WTT and WTW.	Allocation by mass is the most favorable method of considering by- products due to the high quantity produced.
33	(411)	Dale, N., Howes, P., Miller, R., Watson, P.; Advice on the Economic and Environmental Impacts of Government Support for Biodiesel Production from Tallow. DOT ED05914001	2008	Examined the effects of tallow useincluding GHG effects. 2 policy scenarios: biodiesel from tallow is 1) ineligible for support, or 2) eligible for support under EU's RTFO.	Use of tallow would increase CO_2 emissions due to renderers using low sulphur fuel oil as a replacement to tallow. Not a good solution. Tallow is compared relative to other markets like palm oil. Not compared to conventional diesel.
34	(322)	Delucchi, M.; Lifecycle Analyses of BiofuelsDraft Report.UCD-ITS-RR-06-08	2008	Draft report of LEM model results and improvements, with only draft numbers.	LEM model predicts that soy diesel has higher GHG emissions than conventional diesel due to large N_2O emissions from soy fields and large emissions of carbon due to land use change (cultivation).
35	(320)	Delucchi, M.; Important Issues in Lifecycle Analysis of CO ₂ -Equivalent Greenhouse Gas Emissions from Biofuels. Presentation at Workshop on Measuring and Modeling the Lifecycle GHG Impacts of Transportation Fuels at U.C. Berkeley. July 1, 2008.	2008	Presentation on LEM model to discuss how improvements to Nitrogen cycle and climate impacts have been included.	LUC, cultivation is largest source of emissions upstream of biofuels. Soy diesel has higher LCA GHG emissions than conventional diesel.

No.	No.	D - f			
00	(412)	Reference	Year	Outline/Objective	Results
30	()	Mbarawa, M.; Performance, emissions and economic	2008	A societal life-cycle cost (LCC) study was	LCC analysis showed that CSO-diesel blended fuels would not be
		alternative fuels for diesel engines. Renewable Energy		determine the benefits of 25% and 50% straight	However there are some environmental benefits for the blend
		33. 871-882.		CSO in diesel.	
37	(337)	Panichelli, L., Dauriat, A., Gnansounou, E.; Life Cycle Assessment of Soybean-Based Biodiesel in Argentina for Export. Int. J LCA 14, (2009) p 144-159	2008	Argentinian (AR) soy biodiesel pathway w/ regional specificities was developed and compared to Brazillian (BR) and US soy BD, rapeseed BD production in the EU and Switzerland (CH), and palm oil BD from Malysia (MY).	Significant emissions from preparation of land. Can be avoided if deforestation is avoided.
38	(333)	Prieur, A., Bouvart, F., Gabrielle, B., Lehuger, S.; Well to Wheels Analysis of Biofuels vs. Conventional Fossil Fuels: a Proposal for Greenhouse gases and Energy Savings Accounting in the French Context. SAE 2008- 01-0673	2008	Comparison of biofuels to fossil diesel with a base- case scenario and different sensitivity analyses for allocation method and N_2O emission. WTT and WTW	Allocation by mass is the most favorable method of allocation because of high quantity of co products.
39	(34)	Russi, Daniela; An Integrated Assessment of a Large- Scale Biodiesel Production in Italy: Killing Several Birds with One Stone?. Energy Policy 36, (2008) p 1169-118	2008	An integrated assessment for large-scale biodiesel production for Italy to meet EU Directive goals of 3.2MT biodiesel in 2010	1/3 of Italian agricultural land would be needed to meet the EU Directive resulting in considerable increase in food imports and large environmental impacts with decreased Italian energy revenue due to de-taxation of biodiesel.
40 ◆	(303)	S&T2 Consultants; Cheminfo Services Inc., Dr, Heather MacLean; Fugacity Technology Consulting.; Sensitivity Analysis of Biodiesel LCA Models to Determine Assumptions With the Greatest Influence on Outputs. ChemInfo Final Report	2008	Comparison of biodiesel pathways in GREET 1.8 and GHGenius 3.12 in 2007. Comparison limited to data easily extracted from GREET. Second comparison of results from different feedstocks in GHGenius	GREET and GHGenius have several different assumptions, especially in N_2O release. Sensitivity analysis of GHGenius looked at different oil extraction methods, different process fuels. The N_2O sensitivity analysis produces the widest range of differences.
41	(328)	Kalnes, T., Marker, T., Shonnard, D., Koers, K.; Green diesel production by hydrorefining renewable feedstocks. Biofuels-Q4. <u>www.biofuels-tech.com</u>	2008	Description of UOP EcoFining process for Green Diesel (GD) production and compares ER and GWP of GD to bio-, petroleum and syn-diesel.	LCA of green diesel produced from renewable feedstocks indicates relatively high energy efficiency and low GHG emissions.
42 •	(335)	Huo, H., Wang, M., Bloyd, C., Putsche, V.; Life-cycle assessment of energy and greenhouse gas effects of soybean-derived biodiesel and renewable fuels. Argonne ANL/ESD/08-2.	2008	GREET model for biodiesel and different scenarios of renewable diesel from soy oil with different scenarios for allocation procedures.	Biodiesel and both renewable diesels (SuperCetane and EcoFining) showed reductions in fossil energy and GHG with respect to low-sulfur diesel.
∳ Desię	gnates a	study identified as "critical"		Included in Both Energy an Included in GWP chart only Included in Energy chart or Relative GWP results only	d GWP charts (Figures 37 and 38) / (Figure 38) nly (Figure 37) (Figure 39)

Study No.	Feedstock and Production	Location And LCA tool		Scenarios And Method of Co-	Land Use	Reference	GWP*/ Change in GWP relative to		
Ref. No	Method	used	Critical Assumptions	Product Allocation	Change	Fuel	conv. Diesel	EROI**	Other considerations***
1 ₩ (314)	Soybean: Trans- esterification	USA; Not mentioned	Weighted averages for 14 soy-oil producing states. •Energy efficiencies of biodiesel vehicles are identical to conv. Diesel vehicles. • Carbon neutral principle. • Nat'l avg. transport distance 571 mi.	1 with investigation of fossil energy and primary energy using Mass Allocation	Direct: cultivation of land	Petroleum Diesel: GWP: 235.9 EROI: 0.833 Primary and Fossil Energy.	WTW (not incl. tailpipe emissions gm CO ₂ only) B20: 198.9 B100:50.9	Biodiesel: 0.806 (Primary Energy) 3.215 (Fossil Energy)	Wastewater production (L/MJ) Diesel : 0.175 B20: 0.147 B100: 0.0369
2 (321)	Soybean oil: Trans- esterification WTT and WTW	USA; LEM	LEM specific assumptions.	None; Uses combination of expansion and displacement.	Direct LUC in cultivation. Heavy consideration of N rates.	None	None	None	None
3 (402)	Rapeseed Trans- esterification WTW	Europe, LBST E2database for WTT and GM for TTW	Not discussed in detail since only 5% RME blend was investigated. WTW modeling was done for both conventional vehicles and hybrid vehicles.	None discussed	None discussed	Petrol. diesel WTT: ER= .89 GHG=11 WTW in conventional and hybrid vehicle.(/ km) Energy= 1.84- 2.19 MJ/km GHG=140- 166 g/km	WTT: 8+/- 2.5 g/MJ WTW= 140-166 g/km (0% change relative to reference)	WTT= .85 all 0.93 fossil. WTW: 1.95-2.31 MJ/km (increase from diesel)	None Note: not included in figures since results for B5 blend only are given.
4 (403)	Rapeseed (<i>Brassica</i> carinata): Crop Production only	Southern Italy; Not mentioned	 100 km distances data inputs from literature no co-product allocation 	None, no-allocation: comparison of different cropping methods and productivity.	None discussed	None discussed	None discussed	Energy requirement to product crop only.	None
<u>5</u> (339)	Rapeseed: Trans- esterification WTW	Germany; IFEU	 Agriculture assumptions calculated under average German conditions. Base case processing 	One with expanded allocation. Co-product assessment incl. rapeseed honey and meal fermentation to produce biogas.	No land use change reference used is set-aside land w/ fertilizers.	Diesel	2.2 kg CO ₂ eq / Liter RME saved compared to diesel (that emitted in 6L of diesel)	Saves energy required to produce 8L of Diesel.	Considers ACP, OZD, POCP relative impact to diesel. Advantage for diesel for ACP, Nutrient inputs, and OZD. Small POCP benefit for RME.
6 ₩ (331)	Sunflower, Rapeseed, Soybean: Trans- esterification WTT	EU- Italy; Not- mentioned	 Ranges of crop yields are EU average 	Range of values for 3 feedstocks; with or without co-product allocation and a range of harvest yields. Allocation method likely by energy.	Direct land use by crop yield and fertilizer inputs. Must fall within sustainable agriculture.	Comparison of results and to ethanol produced from ligno- cellulose and traditional feedstocks.	N/A	With: Without Allocation Sunflower: 0.4-1.2: 0.3-0.9; Rapeseed: 1.0-1.5: 0.7-1.0; Soybean: 0.7-1.6: 0.2-0.6;	None
7 (404)	Wood (farmed): Choren Process gasification for FTD	Germany— (plant in Freiburg); compliance with DIN EN ISO 14040	 Based on data for 43MW Choren process plant in Freiburg (under construction when published) 	Three scenarios for H_2 production; allocation method not discussed. For self sufficient/ future and partial self- sufficient better than conventional diesel	Not discussed	Conventional Diesel: No value given; other impacts are relative.		Efficiency of Process 64%, 45%, 55%	GWP 91% , 87% and 61 % less compared to conv. Diesel EUP: 29%, 13%, 3% ACP: 42% 27% 5%

Appendix VI-2. Biodistillate Life-Cycle Assessment (LCA) Results

Study		Location		Scenarios					
No.	Feedstock and	And		And	1	Defense	GWP*/ Change in		
Pof No	Production	LCA tool	Critical Assumptions	Rethod of Co-	Land Use	Eucl	GWP relative to	EBOI**	Other considerations***
8	Rapeseed	Sweden:	•40 ha, 1000 ha, and 50,000 ha for	Twelve: 4 types of co-	Direct land use	Comparison	For sm. med. la	For sm. med. la-	ACP=0.019-0.519
₩	(brassica	Not	small, medium and large	product allocation:	change from	of allocation	resp.:	respectively:	EU= 0.0385-0.0862
(324)	napus): Trans-	mentioned	production, respectively.	(energy, economic,	agriculture	method and	Physical	Physical: 3.4, 3.6,	POCP= -5.67-7.15
	esterification		Large scale has high extraction	none, expansion) for	-	facility size.	allocation:	3.5	
	WTT		efficiencies, longer transport	small, medium or		Comparison	40.3,39.5,40.2	Economic:2.8,	(Relative to Diesel, AP and EP
			distances. Small scale-low	large scale production		between	Economic	3.1, 3.2 Nono: 1 9, 2 0	Increased by 79% and 81%.
			short transport distances	lacility.		facility w/		None. 1.6, 2.0, 2.5	POCP reduced by 66%.)
			 Annual vield: 2670 kg/ ha w/ 			physical	No allocation:	Expanded:	Results of sensitivity analysis.
			moisture content of 15% at harvest.			allocation to	87.6, 79.5, 61.9,	-2.74; -2.92;	which varied production factors
			8% moisture after drying with 45%			lit. values for	Expanded: 34.5,	-6.81	by plus or minus 20% not
			oil • Swedish electricity: 48% hydro,			MK1 diesel	32.1, 30.9	Lg, Physical= 4.8	reflected in reported values.
			44% nuclear, 4% fossil fuels, 3%					times higher than	
			I HV of biodiesel = 38 5M l/kg			GWP. 217 g		diesei.	
			Erry of blodieser – 50.5mb/kg			engine (vs.			
						127);			
9	Soybean:	Italy;	 Soybean harvest: 2445 kg/ ha 	Two: co-product	Direct	Commercial	(Including	2.09	1 MJ biofuel = 1.398 MJ primary
(338)	Trans-	Based on	• fuel 116.5 kg/ ha •fertilizer	allocation by mass vs.	agricultural	Diesel Oil D2.	combustion)		energy, 35% of which is derived
	(W/TT)	Emergy	for nitrogen, phosphates, and 51kg/na	none.	impact.	GVVP= 22.2 (12-75%	w. allocation 5.7		From tossil fuels. Additional
	(****)	Odum HT	potassium, respectively			reduction)	19.5		requires a larger amount of
			conversion • Analysis includes			,			resources for final product than
			combustion of fuel65% of						diesel
10	<u> </u>	1.40	emissions in combustion process.			E 11 D 1	N 1/A		× 1
10 	Rapeseed :	Lithuania;	•Ag inputs incl. fuel and fertilizer	Forty: methanol vs.		Fossil Diesel	N/A	RME: 1.04-2.82	None
(302)	esterification	using ISO	Data are specific to Lithuania	fuel: harvest vield:		(presented for		Only showing the	
	WTT	14040-	•Two different ag methods: 1)	different ag methods; ;		comparison)		high and low for	
		14049	mineral fertilizers and drying of	productivity high with				20 scenarios.	
			seed, 2) biofertilizers and seed	hot pressing or low					
11	Sov/ Sunflower:	None	preservation.	With cold pressing.	None	None	None	Sov: 76-03	None
(405)	Trans-	mentioned.	(1500kg/ha vs 2668 kg/ha) but	meal by energy: and w	discussed but	None	None	Sunflower: 46-	None
` '	esterification.	independent	higher oil yield (26% vs 18%)Soy:	and w/o "soy meal"	energy of			.52	
	WTT	w/ literature	• LHV = 37.7 MJ/kg	from sunflower prod.	fertilizers is				
40	Casasia	data.		No glycerine credit.	included.	Diadiaaali	N1/A		Nasa
(406)	Cassava: Ethanol		no pathway for biodiesel: ethanol	method not discussed	NOT DISCUSSED	Compares	IN/A	3.2 (IIUIII NREL)	INOTICE
	production*	China:	1998 NREL study for biodiesel.			cassava			
	P	Not				ethanol			
		mentioned				relative to			
40	Democratica	Finles d	Dete frem Deenvis - start - see "	Oiu investigator		biodiesel.	Democra d El La d	Democra d El l	
13	Rapeseed and		-Electricity split Einland and NG	Six: Investigates	LOOKS at both	Rapeseed vs.	Rapeseed EU-set-	Rapeseed EU-	(NON-RE ONLY)
(334)	NExBTL	plant in	from Russia, rapeseed from EU and	and feedstock origins	set-aside land	GWP: saves	Natural : 44.7	EU Natural : 2.7	GJ primary energy per t of
	processhydro	Poorvoo.)	overseas, and palm oil imported	Allocation method is	for crop growth	1.2-2.5 t CO ₂	Overseas (OS)	OS Natural: 2.2	NExBTL;
	treating WTT		from Malaysian.	rape meal substitution	in both Europe	eq/tof	Natural:56.4	Reference cases	from palm oil: 44 GJ primary
		IFEU	 European electricity split (UCTE) 	ot soy meal from N.	and overseas	NExBTL (33-	Reference Cases	for other uses of	energy per t on NExBTL

Study No.	Feedstock and Production	Location And LCA tool		Scenarios And Method of Co-	Land Use	Reference	GWP*/ Change in GWP relative to		
Ref. No	Method	used	Critical Assumptions	Product Allocation	Change	Fuel	conv. Diesel	EROI**	Other considerations***
			and NG. Palm oil from various countries in international market. Same scenarios as Poorvoo for rapeseed. All feedstock is transported to central Europe.	America (expansion).	in the Reference cases	69%) EROI: 30- 33GJ primary energy saved per t NExBTL. (primary ≠ fossil) (61- 68%)	Palm Oil Nat. forest: 53.4 Food Oil: 33.2 Coconut:62.0 Reduction: t CO2 eq per t NExBTL Rapeseed: 1.2-2.5 Malaysian Palm Oil: 1.4	land. Palm Oil Nat. forest: 8.3 Food Oil: 2.6 Coconut: 1.3	Values reported per t NExBTL. Converted using energy value per ton of fuel.
14	Soybean:	US;	 Boundaries include energy to grow 	Different allocation	Considers	Diesel:	GWP= 49	No credit: 1.16	None
₩ (336)	Trans- esterification WTT	Not mentioned	seed; produce farm machinery and buildings; and, sustaining farmers' households.	methods: no credit, by mass, by economics, and by energy. Also looks at two types of energy ratios.	direct land use change/ release of GHG from fertilizers from land already in production.	GWP: 82.3 (41% reduction) Energy gain 2.9%		Mass: 1.83 Economic: 1.81 Energy: 3.38 NEB (incl. energy in co-prod)= 1.93 ER (energy in biodiesel alone= 3.67	
15	Tallow and	Austria;	Results discussed for Scenario I for	Three: origin of UVO	None	Fossil Diesel:	GWP= 18	None	EUP:.033;
(325)	Used Vegetable Oil (UVO): Trans- esterification WTT	EcoIndicator 99 database	UVO only.	with mass and economic allocation methods.	considered	GWP: 90 (80% reduct.) EUP=0.225 ACP=0.23 ABD=0.054 POCP=0.019			ACP:.21; ABD:.037; POCP:.012
16 (332)	Rape and sunflower seed : Trans- esterification WTT	Italy; Not mentioned	 Yield of 1.8t/ ha and 2.2t/ ha of rapeseed and sunflower seed, respectively. 	Four: co-product allocation by economics vs. none of two feedstocks.	Direct land use cultivation is considered for energy effects- - no emissions calculations.	Comparative between types of biofuel energy.	None	1.3-1.4 – w/o co- products 2.1-1.9 - with co- products for rape and sunflower respectively	More energy GJ/ha NET) w/o co-products Rape= 10.31 Sunflower= 10.17 w/ co-products Rape= 24.96 Sunflower= 28.08
17 (407)	Rapeseed: Trans- esterification (WTT)	Sweden; Not mentioned	Not mentioned	One; allocation method not discussed	Not mentioned	Conventional low-sulfur diesel.	94% reduction		None
18 ⊬	Biodiesel: Trans- esterification of Rapeseed and Sunflower Gasification to DME or syn- diesel of wood- waste (WW),	EU; Program developed by LBST.	Commercially available tech in 2010-2020 time horizon Energy on LHV basis Fertilizer and farming input data from FfE 1998, which has higher N ₂ rates than EU25, but with higher yields. 85% efficiency for process estimated/ depends strongly on performance of FT catalyst.	Biodiesel: Six: three feedstock and two uses of glycerin with expanded allocation. FTD and DME: Six: Three feedstocks and process to DME or Syn-Diesel with energy allocation.	Direct LUC: crops grown on set-aside land otherwise left fallow with grass. GHG breakeven period for converting	Conventional Diesel (and other types of alternative fuels) GWP = 88 gm $CO_2 \text{ eq} / MJ$ fuel (including combustion for	WTT Glycerin as (1)chemical: RME=46.5 /48.0 REE=43.3/ 45.2 SME=24.7 /26.6 as (2) animal feed RME= 51.8/ 53.7 REE =48.0/ 49.7 SME= 30.0 /31.6	WTT (= WTW) Glycerin as chemical.; RME =2.17 REE=2.44 SME = 2.78 as animal feed RME= 1.96 REE = 2.22 SME= 2.44	Economic estimation included. Brief paragraph of threat of increase EUP and ACP potential for biodiesel and lowering of watertable. No calculations.

Study No. Ref. No (307)	Feedstock and Production Method farmed wood (FW), or waste wood via black liguor (BL)*	Location And LCA tool used	Critical Assumptions • Wood conversion processes are made electricity neutral. • Vehicles in WTW are 2010	Scenarios And Method of Co- Product Allocation	Land Use Change grassland to arable land ; Not included for DME	Reference Fuel comparison) EROI= 0.863	GWP*/ Change in GWP relative to conv. Diesel Before/After comb. DME WW: 4.5 / 5.8 FW: 7.0 / 8.1	EROI** DME (incl. E final fuel) WW:16.7 / FW: 16.7 / 356	Other considerations***
							BL: 2.2 / 3.5 Syn-Diesel WW: 4.8/ 5.7 FW: 7.4/ 8.5 BL: 2.4 / 3.4	BL: 33.3 / 269 SynDiesel WW: 14.3 / FW:16.3/ 385 BL: 25 /350	
19 (313)	Average mix of soybean and yellow grease: Trans- esterification WTT	USA; GREET	Average mix of soybean and yellow grease, same as analysis completed for the Renewable Fuel Standard. Uses GREET default assumptions for electricity mixes, etc.	None discussed	Indirect land use change not included in GREET. Cultivation included.	Diesel	67.7 % decrease in CO ₂	None	None
20 (408)	Gasification to FTD of Canola, Tallow, Wood: Trans- esterification, SuperCetane hydrogenation WTW	Canada; GHGenius	None discussed	None discussed	None discussed	Conventional fuels and other alternative fuels to determine best option.	N/A	None discussed	None
21 (326)	None for biodiesel WTW	The Neth- erlands; Swiss Ecolnvent V1.1 data	None discussed for biodiesel	Different allocation methods and allocation coefficients	None dicussed	None: comparison of allocation methods w/o assessment of results.	N/A	Does not assess total values	None
22 (330)	Rapeseed, : Trans- esterification WTW (zero emissions during combustion)	Sweden; Matlab/ Simulink, with ISO- 14040	•25km transport distance between farm and plant • 1000 ha cultivated• Includes fuel use in farm equipment, emissions assumptions for farm equipment provided. WTW, zero emission during combustion = WTT	Two: co-product allocation by economics vs. none.	Direct land use only.	Conventional Diesel. Also, comparison of ethanol and biogas use. GWP: 79.5	21.8 (73% decrease vs. diesel, also, 28% less than ethanol and 38% less than biogas.	With/ Without Allocation 8.3 / 4.2	EUP: 25.46 kg O2 eq/ MJ fuel (79% increase) ACP: .827 (31% increase) 8.5% of 1000 ha or land used for fuel production. Economic: .047 Euro for RME
(342)	Rapeseed: Trans- esterification	Location not discussed; SimPro V6.	 Process plant and equipment construction not incl. •Alcohol to oil ratio from 3:1- 6:1• Variety of process-based differences/ assumptions. • Biological catalyst data from lab experiments. • Cases: 1: NaOH cat, MeOH, HR. 2: Bio-cat, MeOH, 3: NaOH, MeOH, LR 4) NaOH. EtOH.HR. 5) bio-cat, EtOH. 	Five: process fuel (methanol vs. ethanol); catalyst type (NaOH cat vs bio-cat) ; and alcohol recovery efficiency (high recovery HR vs low recovery LR). Mass allocation of glycerol	Direct LUC ag inputs.	None: comparison of catalysis methods and other process differences.	Case 1: 153 Case 2: 149 Case 3: 161 Case 4: 151 Case 5: 147 (Converted using 27.1GJ in 1000kg biodiesel)	None	(gm eq/ MJ fuel) EUP: 1.37-1.39 ACP 1.08-1.17 ABD: .494664 OZD: 2.0E-5-3.3E-5; HT: 4.95-6.79; H2O tox: .458-1.55

Study No. Ref No	Feedstock and Production Method	Location And LCA tool used	Critical Assumptions	Scenarios And Method of Co- Product Allocation	Land Use Change	Reference Fuel	GWP*/ Change in GWP relative to conv. Diesel	EROI**	Other considerations***
24 (178)	Soybean : Eni Ecofining WTT	Western Europe; ISO 14040 with data from SimaPro.	 Inventory data from NREL study (Sheehan 1998) includes cultivation, harvesting, and extraction w/ intermediate transportation steps. Transp. to end user is omitted Scenario A: H₂ is typical refinery blend. Scenario B: H₂ by conversion of green-diesel byproducts propane and naphtha 	Two: method of H ₂ production. Allocation method by mass.	None mentioned: N ₂ O emissions are neglected.	Diesel and Biodiesel. GWP 85.6 EROI: 0.78	Biodiesel= 23.6 Grn Diesel A=14 Grn Diesel B=12.7 Improvement Biodiesel = 62.0; 72.4% Green diesel A= 71.6; 83.6% Green Diesel B= 72.9; 85.1%	Biodiesel= 3.0 Grn Diesel A=3.4 Grn Diesel B=5.0 From Palm Oil: Biodiesel= 4.0 Grn Diesel A=5.0 Grn Diesel B=7.7	None
25 (181)	Soy oil: Conoco Philips-hydro treating WTT	US; Not mentioned	Not discussed	Summary of hydrotreating/ renewable diesel technologies.	Not discussed	Petroleum Diesel	COP soy 56% UOP soy 74% NExBTL rape 69%	Not discussed	None
26 (327)	Soybean : Trans- esterification WTT	US (Colorado); Not mentioned	Not described in detail * Delucchi and Lippmann CO ₂ emissions data • Emissions include driving cycle • consumption of CO ₂ by photosynthesis not included	Range for One feedstock: based on percentage displacement of transportation needs. Allocation method not discussed.	Not mentioned	Petroleum Diesel: GWP: 26 gm/MJ fuel Petroleum Diesel: GWP: 26 gm/MJ fuel EROI=11.1 (uses NREL but subtracts NG extraction energy.	gm CO ₂ / MJ fuel 21-26 Saves 0-5 gm CO ₂ / MJ fuel	1.32 (compared to 11.1 for conventional diesel)	H ₂ 0 : 900 gal/ gal fuel or 6900 gal/ MMBTU fuel Land to displace 10, 25, 50% of transportation energy: 253M, 380M, 1.2 B acres
27 (176)	Vegetable Oil: NExBTL hydrogenation	Europe/ Finland; Not mentioned	None discussed/ LCA briefly discussed in paper • Hydrogen produced from natural gas	None discussed	Not discussed	Fossil diesel.	40-60% lower than fossil diesel	Not discussed	None
28 (329)	Jatropha: Trans- esterification WTT	Thailand; Not mentioned	 Based on 1 ha of jatropha farming for 20 years 2/ 1100-3300 trees/ ha. Best case and worst case scenarios for diff. inputs. Biodiesel factory sited close to refinery; no transportation Average biodiesel from jatropha yield is 2.7 ton/ha/year for best case It takes 2-3 years for jatropha trees to reach full yield 	Over 20: Co-product yields; energy efficiency, and harvest yields. Allocation by energy.	Direct land use impacts include preparation: plough, harrowing, and furrowing.	None	N/A	Range of 0.53-11.99 (Average of all cases 4.77)	Net energy gain= 4720 GJ/ ha
29 (409)	Palm oil: Trans- esterification WTT	Europe; IFEU	 Yield of both 3.5 and 4.0 tones palm oil/ ha per year. Investigates direct LUC of natural forest, fallow land and existing plantations of other crops like coconut and rubber. 	Not discussed	Cultivation of different types of land.	Diesel; avoided emissions are estimated. (30% avoided)	PME, natural forest, 7.3 t CO_2 eq/ ha*a: equivalent to 3.2 t CO_2 eq/ ha *a avoided.	Not discussed	-10 GJ/ ha*a, savings from conv. Diesel: 150 GJ/ ha*a

Study No. Ref No	Feedstock and Production Method	Location And LCA tool used	Critical Assumptions	Scenarios And Method of Co- Product Allocation	Land Use Change	Reference Fuel	GWP*/ Change in GWP relative to conv. Diesel	EROI**	Other considerations***
30 (341)	Straw or short- rotation willow coppice (Salix): Gasification	Sweden, organic farming; Not mentioned	 Tech. feasible w/in 10-15 yr cultivation on 1000 ha of land, 100 km transport distance, trucks use fuel studied. Feedstock transported to processing plant, fuel back to farm. Capital goods production not included. Organic farming w/ 7 year rotation, Nitrogen supplied by nitrogen fixing plants planted every two years. Yield of Salix est. 6300kg/hayr. 	Four: two feedstock; process to DME or FTD. Uses economic allocation.	Direct LUC: N fertilizers and land for each feedstock which result in N ₂ O emissions for cases when most land was used.	Conv. diesel: FTD for straw/ salix: GWP =94.0/84.9% decrease. ACP: 55.7%/ 51.2% decrease. EUP: 26.7/ 16.2% decrease.	gm CO ₂ equivalents per functional unit for Straw/ Salix respectively: FTD= 9.3/ 23.8 DME= 8.2/ 26.0 Functional unit is the amount of fuel needed to cultivate 1000 ha of land.	from Straw/ Salix, respectively FTD = 8.9 / 9.6 DME = 10.1/ 10.0	EUP (in O₂ equiv. / functional unit) FTD =9099/ 8832 DME =7728/8965 ACP FTD = 554/ 610 DME = 409 / 578 for straw/ Salix respectively Economic FTD €30780 DME €32040
31 (318)	Maize, Rapeseed, Sugar cane: Harvesting	Not specific; Not mentioned	 Not a full LCA leaves out fossil fuel use and co-products Conversion factor of 3-5% of newly applied N-fertilizer to N₂0, higher than IPCC factor of 1%. 	None Harvesting only to look at Nitrogen cycle.	Nitrogen cycle specific	None	Relative warming potential of biodiesel from rapeseed is 1.0- 1.7	Not discussed	None
32 (410)	Rapeseed : Trans- esterification WTT	Belgium; Simapro 7.1 databases and Eco- Indicator 99	 Function unit was transport over 100 km for mid-size, recent car. Specific local data for Belgium CO₂ from combustion of biofuels is not taken is assumed to be net neutral with the uptake process in the natural cycle. Biodiesel combustion results in a net increase in NOx emissions. 	Two: co-product allocation by expansion vs. none.	Qualitative assessment- 5.5 vs 12.8 m ² for 100 km transportation 'global impact' for RME vs. Bio-ethanol respectively	Fossil diesel (also compare to petrol and bio-ethanol) ACP and EUP combined shows 32% decrease for biodiesel.	Relative results only 76% decrease from diesel	Relative results only	Global impact: RME shows 59% improvement in comparison to fossil diesel, Improvement would be 18 without valorization of by - products.
33 (411)	Tallow: Trans- esterification WTT	EU; Not mentioned	 Alt. supply of bi0 Alt. supply of oleo chemicals in scen. 2 is from rendering 	Two: feedstock. Allocation method not discussed.	Deforestation for palm in far east is discussed, but not quantitative.	Displacement of tallow into biodiesel production relative to other types of biodiesel.	increased emissions to 974 kg CO₂ eq/ tone tallow displaced	N/A	None
34 (322)	Soybean: Trans- esterification WTT and WTW	USA; LEM	LEM specific assumptions. Reported values are converted using reported density of 0.887 gm/mL and HHV of 40.37 MJ/kg. WTW for HDV with 3mpg.	Draft numbers only. Combination of expansion and displacement	Direct cultivation. N ₂ O rates.	Diesel. (4157 gm/ mi)	125.341 (6361 gm/mi)	.949	Draft numbers only, but indicated 50% increase in CO ₂ emissions.
35 (320)	Soybean: Trans- esterification WTT and WTW	US; LEM	LEM specific Nitrogen cycle	No scenarios: Combo of expansion and displacement	Direct impacts; N ₂ O rates, carbon sequestration.	Diesel.	Preliminary results only, not to be cited.	N/A	None
36 (412)	Clove stem: Distillation into CSO, WTW	Tanzania; Not mentioned	 Diesel Isuzu is 4cylinder, 4-stroke naturally aspirated DI CSO is used directly as a fuel. 	Two: different blends of CSO with fuel. No allocation method discussed.	None discussed	Pure diesel, and blends of diesel w/ straight CSO (no processing to biodiesel)	50% blend results in 7% increase in total emissions; the 25% blend results in 1% decrease.	Not discussed	CSO is more expensive

Study No. Ref No	Feedstock and Production Method	Location And LCA tool used	Critical Assumptions	Scenarios And Method of Co- Product Allocation	Land Use Change	Reference Fuel	GWP*/ Change in GWP relative to conv. Diesel	EROI**	Other considerations***
37 (337)	Soybean: Trans- esterification WTT	Argentina; Ecoinvent	Argentinean regional specificities— B100 used in a 28t truck in CH (w/ .27 and .25 kg/km fuel economy for biodiesel and fossil diesel, resp.) 1 st and 2 nd class soybean in reduced and conventional tillage. 2591 kg/hr yr-N only applied to 1 st class.	Economic allocation- based on internat'l prices for export, but national prices for glycerin.	Cultivation of land use is included- only direct deforestation.	Fossil low sulfur diesel (and biodiesel produced in other countries)	WTT: 48.9	WTT:2.29	EUP, ACP, H ₂ O tox, HT, and TE (terrestrial toxicity)
<u>38</u> (333)	Rapeseed and Sunflower: Trans- esterification WTT and WTW	France; TEAM database	 Carbon neutral principle- no CO₂ released during combustion. WTT=WTW No land use change WTW analysis w/ Belingo Vehicle on normalized European driving cycle (NEDC) 	Two: Type of feedstock with expanded allocation.	Direct land use considers fertilizers and direct ag inputs. No indirect changes.	Diesel (with comparisons for EtOH and gasoline also) GWP (WTW) Rape: 80% Sunflower 78%	WTT Rape: 12 Sunflower: 18 Diesel: 7 WTW Rape: 12 Sunflower: 18 Diesel: 81	For WTT: Rape ~ 3.3 Sunflower ~2.7 Diesel ~7.7 For WTW: Diesel = 0.885, Rape, Sunflower stay the same	None
39 (34)	% 80 Rapeseed , % 20 Sunflower: Trans- esterification WTT	Italy; Not mentioned	 Linear trend in oil demand to 2010 Imported Biodiesel is from Hungary Oil seeds cultivated in abandoned lands; will not replace food crops Domestic oil seeds replace equal shares of fodder plants and cereals All biodiesel production is exempt from taxes Oil seeds are cultivated with intensive agricultural methods 	Two: origin of feedstock with expanded allocation.	Direct land requirement for growing crop is considered.	Fossil Diesel, 1.1% reduction in 2004 emissions levels.	Domestic: 35.8 Imported: 15.4 =1.1% reduction in 2004 levels	Uses 2.5 from Bernesson et al. 2004 for analysis	2% reduction in energy dependency 3.2 MT biodiesel req'd to displace 5.75% total energy demand in 2010. 3.7 M ha req'd, (26% of agricultural land). Economic: 4.8% loss of total energy taxes and 0.3% loss of total revenues.
40 ⊻ (303)	Soybean and Canola: Trans- esterification WTT and WTW	Canada and USA; GREET and GHGenius	Year 2007 Results on a HHV basis GHGenius includes energy required to manufacture farm equipment; GREET does not. Different land-use calculation in each Sensitivity analysis of paper incl. of different oil extraction methods, co- product allocation. Does not use zero combustion emissions	One for GHGenius vs. GREET comparison. GHGenius test: Two feedstocks, with multiple sensitivity analysis ranges. • GHGenius: combo of expansion and displacement; GREET allocation selection.	GREET: emissions calculated for N ₂ O from applied N. GHGenius also includes N ₂ O created when seed N is fixed. Detailed discussion on potential effects of indirect LUC.	Comparison of two different model results, and compare to fossil diesel. Diesel: After Combustion (88.7-89.7) Soy: 60-71% Canola: 75- 78% EROI=4.2594	2002 US scenarios GREET = 33.7 GHGenius= 29.7 For GHGenius before (after combust.): Soy= 24.2 (26.0) (N ₂ 0 sensitivity 18-35) Canola= 17.7-19.3 (19.5-21.1) (N ₂ 0 Sensitivity 25-42) Yellow Grease - 4.4 (-2.7) Tallow= -6.6 (-4.9)	GHGenius CAN= 3.82 GHGenius US = 3.92 GREET US = 1.84 GHGenius Comparison Soy = 3.8119 Canola= 3.9594	None
41	Rapeseed (RSO), Palm Oil (PO), Tallow: Ecofining for Green Diesel (GD)	Average European. SimaPro data w/ data for UOP processes.	 GHG contributions from N₂O, CO₂, and CH₄. Combustion emissions are not incl (GD comb: CO₂ only from renewable oils, no offsets; Biodiesel combustion incl. only MeOH-derived 	4 scenarios for biodiesel, 4 for GD— different feedstock and if biogas (BG) is used as a fuel. No allocation for palm	N ₂ O emissions are included, but no sensitivity to them. LUC out of scope.	GD compared to biodiesel from transesterifica tion and to low sulfur	Biodiesel: RSO: 2.4 PO: 2.4 PO w. BG: 2.5 Tallow: 4.2 GD:	Biodiesel: RSO: 46 PO: 54 PO w. BG: 31 Tallow: 20 GD:	

Study No. Ref No	Feedstock and Production Method	Location And LCA tool used	Critical Assumptions	Scenarios And Method of Co- Product Allocation	Land Use Change	Reference Fuel	GWP*/ Change in GWP relative to conv. Diesel	EROI**	Other considerations***
(178)			CO ₂ of fossil origin). •Farming rapeseed and palm. Tallow considered waste from meat plants. Only emissions for transport	oil. Expanded allocation for rapeseed meal. Energy and Economic for tallow.		petroleum. ER= .787 GWP= 84	RSO:2.4 PO:2.7 P.O w. BG: 2.9 Tallow: 9.1	RSO: 41 PO: 48 P.O w. BG: 26 Tallow: 5	
42 (335)	Soy-oil: WTW 1. Trans- esterification and hydro- genation (2. SuperCetane and 3. GreenDiesel from Ecofining)	GREET (and ASPEN plus)	 Boundaries incl. farming activities, transportation, oil extraction, fuel production, and use. N₂O and other emissions factors based on IPCC 2006 estimates. Detailed description of fertilizer use and rates Energy reported is fossil energy. Total energy also included in study. 	12 scenarios for 3 production methods and 4 co-product allocation. Co-prod methods: 1. Displacement 2. by Energy 3. by mkt. value 4. hybrid of displacement and allocation.	No potential LUC is considered. Only emissions rates from direct cultivation.	Low Sulfur Diesel. ER= .826 GWP = 95 GWP Biodiesel: 66- 94% RDI- 62-130% RDII- 66-74%	Biodiesel 1) 5, 2)30, 3) 32, 4) 5 SuperCetane 1)-30 2) 32 3) 36 4) -20 Ecofining 1) 30, 2) 24, 3)25, 4) 32	Biodiesel: 1) 5.2, 2) 2.5, 3) 2.4. 4)5.2 RDI- SuperCetane 1) 8.3, 2) 2.6, 3)2.2, 4) 2.2 RDII-Ecofining, 1)1.8, 2)2.9, 3)2.8, 4) 1.7	

Included in Both Energy and GWP charts (Figures 37- and 38)	
Included in GWP chart only (Figure 38)	
Included in Energy chart only (Figure 37)	
Not included in any chart	

*Global Warming Potential: GWP in gm CO₂ equivalent/ MJ fuel

** Energy Return on Investment: (EROI) WTT reported as Energy in Fuel (LHV) / Life-cycle energy inputs. WTW reported Life-cycle energy input for 100 km unless otherwise stated. ***Other Considerations:

Eutrophication: (EUP) in g PO_4^{3-} equivalents/ MJ fuel unless otherwise stated

Acidification: (ACP) in g SO₂ equivalent/ MJ fuel unless otherwise stated. Abiotic Depletion: (ABD) in g antimony (Sb) equivalent/ MJ fuel.

Photochemical Ozone Creation Potential: (POCP) in mg ethylene (C_2H_4) equivalent/ MJ fuel

Ozone Layer Depletion: (OZD) in g CFC -11 equivalent/ MJ fuel.

Human Toxicity: (HT) in gm 1,4 DB equivalent/ MJ fuel.

Fresh Water Aquatoxicity (H_2O tox) in g 1,4 DB equivalent/ MJ fuel.

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