

# Improving the Properties of Vegetable Oils and Fats for Use as Biodiesel

## Introduction

The idea of using vegetable oil as a substitute for diesel fuel was demonstrated by the inventor of the diesel engine, Rudolph Diesel, around the year 1900. Since that time vegetable oil-based fuels have been examined as possible substitutes for diesel fuel by many researchers (1). Although the concept of vegetable-oil fuels has been periodically introduced, it has not been seriously considered, mostly because, even though short-term tests are satisfactory, long-term use of neat vegetable oils leads to serious engine problems (2). The energy crises of the 1970s and early 1980s, however, have led to worldwide efforts to develop alternative fuels such as vegetable oil-based diesel fuel. In the United States, vegetable oil-based diesel fuels were originally sought as emergency fuels in case of another petroleum shortage. Over the years, the focus has broadened considerably, driven by the intent to utilize a domestic, renewable resource that provides environmental benefits with lower emissions. Legislation such as EPACT (the Energy Policy Act of 1992) and the Clean Air Act, which requires the use of low-emission fuels, has provided additional impetus to these efforts. Therefore, vegetable oil-based fuels are now being utilized or tested in various niche markets such as urban bus fleets as well as in mining and marine engines. These environmental concerns and regulations override the higher price of vegetable oil-based fuels, which would otherwise render them economically unattractive.

In addition to economic impediments, the use of vegetable oil-based diesel fuel has encountered some difficult research problems that are a result of the properties of vegetable oils and their component triglycerides and fatty acids. Researchers around the world have attacked these problems, but several remain to be solved. Although the term *biodiesel* lacks a clear definition, it is often associated with the transesterification products of vegetable oils and methanol: the low-viscosity methyl esters of fatty acids.

This chapter discusses past and present research on vegetable oil-based alternative diesel fuels, biodiesel, with emphasis on the work conducted in the laboratories of the Agricultural Research Service of the U.S. Department of Agriculture.

## Vegetable Oils as Diesel Fuels

The suitability of fatty compounds as diesel fuel is demonstrated by several properties. For example, the heat contents of various vegetable oils are nearly 90% that of No. 2 diesel fuel (3,4), the transportation diesel fuel (DF) usually used as reference for vegetable oil-based fuels. The heats of combustion of fatty esters and triglycerides (5) as well as fatty alcohols (6) have been determined. Generally, the heats of combustion will increase with chain length.

A prime indicator of diesel fuel quality is the cetane number (CN). The CN is related to the ignition delay time of a fuel in the combustion chamber. The shorter the ignition delay time, the higher is the CN, and vice versa. The two standards for CN are hexadecane (cetane), with a CN of 100, and 2,2,4,4,6,8,8-heptamethylnonane (HMN), with a CN of 15. Generally, the CN of fuels used in engines is in the range of CN 40–50, with the ASTM (ASTM D975) minimum specification a CN of 40. The CNs of vegetable oils are in the range of 35–50 (3). Generally, vegetable oils have better ignition quality than their CNs imply (7,8). The CNs of fatty alcohols and methyl esters can be predicted from their physical properties, with boiling point giving the closest correlation (9).

Every diesel fuel, conventional or vegetable oil-based, experiences an ignition delay upon injection into the combustion chamber, which is the basis of CN measurements. Obviously, the fuel passes through a temperature and pressure gradient directly after injection but before combustion begins. Chemical reactions already occur in this precombustion phase. In one study (10), unsaturated triglycerides (triolein, trilinolein, and trilinolenin) were studied in a reactor at temperatures up to 400°C in both air and a nitrogen atmosphere simulating conditions in a diesel engine. The compounds identified as arising in this phase were fatty acids of different chain lengths, various aliphatic hydrocarbons, and smaller amounts of other compounds such as aldehydes. The parent acids, however, were the most prominent compounds detected in the precombustion mixture. In a second parallel study (11), tripalmitin and tristearin were studied along with the three unsaturated triglycerides at temperatures of 450°C. In addition to (mainly unsaturated) aliphatic hydrocarbons and unsaturated aldehydes, various aromatics, including benzene, toluene, and polyaromatic hydrocarbons, were detected. At this temperature no fatty acids, glycerol, or acrolein (a

decomposition product of glycerol) were detected. Extensive decarboxylation occurred, showing that the oxygen in biodiesel methyl esters does not necessarily contribute to its combustion as an oxygen enhancer.

Other important fuel-related properties of vegetable oils are viscosity, cloud point (CP), pour point (PP), surface tension, and volatility. Vegetable oils have considerably higher viscosities (10–20 times) than conventional DF as well as higher cloud and pour points. Table 1 lists important fuel properties of some vegetable oils used as sources of biodiesel.

The high viscosity of vegetable oils, with resulting poor atomization in the combustion chamber, has been identified as a major cause of engine problems such as nozzle coking and engine deposits (12,13). Four different solutions to the viscosity problem have been researched:

1. Microemulsification
2. Transesterification
3. Dilution
4. Pyrolysis

Currently, the most commonly applied solution to the viscosity problem is transesterification. The resulting esters, usually methyl esters, have significantly lower viscosities (about twice that of DF2) but also problematic low-temperature properties (Table 2). Formation of esters and their low-temperature properties are discussed below.

## Microemulsification

Microemulsions are defined as transparent, thermodynamically stable colloidal dispersions in which the diameter of the dispersed-phase particles is less than one-fourth the wavelength of visible light. Microemulsification was

**Table 1**  
Selected Fuel Properties of Some Vegetable Oils<sup>a</sup>

Oil	Viscosity <sup>b</sup> (mm <sup>2</sup> /s)	Cetane no.	Gross heat of combustion (kJ/kg)	Cloud point (°C)	Pour point (°C)
Castor	297.0	?	37,274	None	-31.7
Corn	34.9	37.6	39,500	-1.1	-40.0
Cottonseed	33.5	41.8	39,468	1.7	-15.0
Crambe	53.6	44.6	40,482	10.0	-12.2
Linseed	27.2	34.6	39,307	1.7	-15.0
Peanut	39.6	41.8	39,782	12.8	-6.7
Rapeseed	37.0	37.6	39,709	-3.9	-31.7
Safflower	31.3	41.3	39,519	18.3	-6.7
High-oleic safflower	41.2	49.1	39,516	-12.2	-20.6
Sesame	35.5	40.2	39,349	-3.9	-9.4
Soybean	32.6	37.9	39,623	-3.9	-12.2
Sunflower	33.9	37.1	39,575	7.2	-15.0
No. 2 Diesel fuel	2.7	47	45,343	-15.0	-33.0

<sup>a</sup>Data taken from Ref. 3.

<sup>b</sup>Viscosity determined at 38°C.

**Table 2**  
Fuel Properties of Some Soybean Esters<sup>a</sup>

Fuel	Viscosity <sup>b</sup> (mm <sup>2</sup> /s)	Cetane no.	Gross heat of combustion (kJ/kg)	Cloud point (°C)	Pour point (°C)
Methyl soyate	4.08	46.2	39,800	2	-1
Ethyl soyate	4.41	48.2	40,000	1	-4
Butyl soyate	5.24	51.7	40,700	-3	-7
#2 Diesel fuel	2.07	47.0	45,343	-15	-33

<sup>a</sup>Data taken from Refs. 31 and 32.

<sup>b</sup>Viscosity determined at 40°C.

among the first solutions pursued for the viscosity problem of vegetable oils (14). The components of microemulsions can be conventional diesel fuel, vegetable oil, an alcohol, a surfactant, a cosurfactant, and a cetane improver. Microemulsions can be distinguished as nonionic or ionic microemulsions depending on the components (usually the amphiphile or surfactant) present. Microemulsions containing an ionic surfactant (for example, a quaternary ammonium salt) are termed ionic, an example of which is soybean oil solubilized with methanol by triethylammonium linoleate and 2-octanol. An example of a nonionic microemulsion that is also detergentless is soybean oil with methanol solubilized by *n*-butanol and oleyl alcohol (15).

Generally, microemulsification shows considerable promise for providing low-viscosity fuel blends containing substantial quantities of vegetable oil. Engine performance tests on those fuels tested (16,17) with large amounts of low-molecular-weight alcohols showed that:

- Nonionic microemulsions produced nearly as much engine power as did DF.
- The nonionic fuel gave slightly higher thermal efficiency and engine power.
- Microemulsions gave lower exhaust temperatures, less exhaust smoke, and lower CO and NO<sub>x</sub> emissions than observed for DF.
- Microemulsion fuels burned faster than DF.

A soybean oil/DF microemulsion managed to pass the 200-hour Engine Manufacturer's Association (EMA) tests, but there were indications that failure would have occurred had the engine been run on the fuel for a slightly longer time (17). A microemulsion consisting of soybean oil:methanol:2-octanol and a cetane improver also passed the 200-hour EMA test.

## Transesterification (Mono-Alkyl Esters)

The advantages of vegetable oil mono-alkyl esters for solving the viscosity problem and accompanying engine problems were recognized in the early stages of renewed interest in biodiesel (13). Subsequent studies on transesterification showed that in homogeneous catalysis, base-catalyzed transesterification is much more rapid than acid-catalyzed transesterification (18,19). At 32°C, transesterification was complete in 4 h when using NaOH or

NaOMe. At 60°C and a molar ratio of at least 6:1 (alcohol:oil) and with fully refined oils, the reaction was complete in 1 h to produce methyl, ethyl, or butyl esters. The reaction parameters investigated were molar ratio of alcohol to vegetable oil, type of catalyst (alkaline vs. acidic), temperature, reaction time, degree of refinement of the vegetable oil, and effect of the presence of moisture and free fatty acid. Although the crude oils could be transesterified, ester yields were reduced because of the gums and extraneous material present in the crude oils.

Transesterification is a reversible reaction. The transesterification of soybean oil with methanol or 1-butanol proceeded with pseudo-first-order or second-order kinetics depending upon conditions used, whereas the reverse reactions were second-order (19).

Recently, an alternative transesterification method for the production of mono-alkyl esters (AE) has been reported that involves the use of lipases as transesterification biocatalysts. In these studies, several commercially available lipases were screened for their abilities to transesterify the triacylglycerols (TAG) of sunflower (20), olive, soybean, and rapeseed oil and tallow (21) with short-chain alcohols to their mono-alkyl ester derivatives. For methanolysis reactions, the lipase from *M. miehei* (Lipozyme™) was the most effective in converting the TAG to their corresponding methyl ester derivatives. The same enzyme was also effective for preparation of the ethyl and isobutyl ester derivatives of the same TAG (21). Transesterification reactions of tallow and soybean oil with isopropanol and 2-butanol, however, gave the highest conversions when the lipase from *C. antarctica* (Novozyme™ 435) was used as the biocatalyst (21). For production of alkyl esters from triglycerides and secondary alcohols, the addition of small amounts of water to the reaction medium improved conversions. The opposite effect was observed for methanolysis, which was extremely sensitive to the presence of water. Conditions were subsequently established for preparing these mono-alkyl esters from primary alcohols to yield over 98% conversions, and from secondary alcohols to yield over 95% conversion (21). When applied to greases with varying fatty acid contents, secondary alcohols were extremely effective in converting high-free fatty acid feedstocks to their respective alkyl esters (21,22).

The analysis of the transesterification reaction products has also received attention. Glyceride mixtures have been analyzed by thin-layer chromatography with flame ionization detection (TLC/FID) (23), which was also used in the studies on the variables affecting the yields of fatty esters from transesterified vegetable oils (18). Transesterification reaction mixtures were analyzed by capillary gas chromatography (24), which accounted for esters, triglycerides, diglycerides, and monoglycerides in one run. Another report included analysis of glycerol by GC (25). In both papers (24,25) the hydroxy groups of the glycerides and glycerol were derivatized by silylation with *N*-methyl-*N*-trimethylsilyltrifluoroacetamide. Recently, a high-performance liquid chromatographic (HPLC) method has been developed for quantifying reaction mixtures obtained from transesterified fats and oils (26). Advantages of the method are that deriva-

tization of the sample is not required; analysis time is under 30 min; and all neutral lipid classes, including alkyl esters, free fatty acids, triglycerides, 1,2- and 1,3-diglycerides and 1(2)-monoglycerides, are readily quantified.

### Properties of Mono-Alkyl Esters

Table 2 compares the essential fuel properties of methyl, ethyl, and butyl soyate. In each case, the viscosity is decreased to about twice that of DF (for DF values, see Table 1). Note also that the CNs are improved, now being higher than that of DF.

The most commonly used esters are the methyl esters (ME), which are now commonly equated to the term *biodiesel*. For economic and availability reasons the esters are usually blended with conventional DF; a blend ratio of 80% DF/20% ME by volume is the most common. These blends show the lower emissions observed with the neat ME.

The esters, however, exhibit low-temperature properties that are even less desirable than those of the neat triacylglycerol esters (oils), such as relatively high cloud and pour points. The high-melting saturated esters are responsible for these characteristics. The cloud point is the temperature at which a material becomes cloudy because of the formation of wax crystals and other solids, especially saturates. These solids can clog fuel lines and filters. With decreasing temperature, more solids are formed, and eventually the material reaches the pour point, which is the lowest temperature at which it still pours. Two methods exist for testing low-temperature filterability: the low-temperature flow test (LTFT, used in North America) and the cold-filter plugging point (CFPP, used in Europe). Low-temperature filterability tests are necessary because they correlate better with operability tests than CP or PP (27).

Blends of esters with diesel fuel, usually 80%DF and 20%ME, are currently the most common form of biodiesel. Studies on neat methyl soyate (MS), MS blends with DF, and admixtures with 5–30% methyl tallowate (MT) have been conducted (28). Cold-flow properties were not greatly affected by admixing MT. The LTFT and CFPP of fuel formulations containing at least 10 vol% methyl esters show a nearly linear correlation with CP. Statistical analysis showed a strong 1:1 correlation between LTFT and CP. Therefore, effective approaches to improving cold-flow properties should initially lower CP. In this regard, winterization of methyl soyate lowered its CP to -16°C (28); recovery of liquid esters, however, was significantly reduced.

Another approach for improving low-temperature properties is the formation of branched-chain esters (29). The isopropyl and 2-butyl esters of soybean oil lowered the crystallization onset temperature ( $T_{CO}$ ), which is 2–7°C higher than the cloud point, by 7–11°C and 12–14°C, respectively, compared to the corresponding methyl esters, as determined by DSC (differential scanning calorimetry). Similarly, the low-temperature properties of a series of mono-alkyl esters derived from tallow and recycled greases (5–30% free fatty acid content) were determined both for the neat esters and as 20% blends in DF (30). Here also it was found that branching in the alcohol moiety of the esters improved their

low-temperature properties. For example, the pour point of isopropyl tallowate was 9°C lower than that of the *n*-propyl ester, and that of the 2-butyl ester was 6°C lower than the *n*-butyl ester. For the tallow ester series, cloud points were 8–17°C lower for the branched alkyl (isopropyl, isobutyl, and 2-butyl) esters compared to the normal alkyl esters (methyl to *n*-butyl). Blending the tallow esters (20%) in diesel fuel produced a leveling effect in both PP and CP, with both being reduced by 14–22°C. For alkyl esters derived from greases, the pour points and cloud points were better than their tallow counterparts. The PPs and CPs of these esters were comparable to those of methyl soyate (-2 and 0°C, respectively). This is understandable, because the greases are blends of animal fat and vegetable oils. Blending the grease alkyl esters in diesel fuel gave PP and CPs similar to that of methyl soyate in diesel fuel.

In general, the branched alcohol tallow esters did not have improved cold filtering plugging points over those of the normal alcohol tallow esters (Table 3). Blending of these esters in diesel fuel, however, decreased their CFPPs on average by 20°C. Blending of the alkyl ester derivatives of greases gave better or similar CFPP compared to methyl soyate and a blend of methyl soyate (80%) and methyl tallowate (20%). Table 3 also lists the low-temperature flow test (LTFT) results for the tallow alkyl ester derivatives. The branched alkyl tallow esters did not show much difference from the normal tallow esters, and, based on the LTFT test alone, only the ethyl and butyl esters have potential as biofuels. Esters derived from greases, both branched and normal, gave satisfactory LTFT results both in the neat form and blended in DF. However, the former LTFTs did not compare favorably when compared to methyl or ethyl soyate.

## Dilution

A 75:25 (vol%) petrodiesel/sunflower oil blend had a viscosity of 4.88 mm<sup>2</sup>/s at 40°C. The blend was not recommended for long-term use in the diesel engine. A 75:25 (vol%) petrodiesel/high-oleic safflower oil blend with a viscosity of 4.92 mm<sup>2</sup>/s passed the 200-hour EMA test.

The different results were attributed to the degree of unsaturation of the vegetable oil (32). The more unsaturated oil (sunflower) that accumulates in the crankcase and hot engine parts tends to oxidize and polymerize due to its reactivity. Accumulation of such products in the lube oil could lead to lubricant thickening. A lube oil change is called for by the EMA test after 100 hours, and at that time the viscosity of the lube oils had not varied greatly in either test.

## Pyrolysis

Of the possible solutions to the viscosity problem of vegetable oils, pyrolysis has been the least studied. Soybean oil pyrolyzed distillate, which consists mainly of alkanes, alkenes, and carboxylic acids, has a CN of 43, exceeding that of soybean oil (37.9) and the ASTM minimum value of 40 (33). The viscosity of the distillate was 10.2 cSt at 38°C, which is higher than the ASTM specification for DF (1.9–4.1 cSt) but considerably below that of soybean oil (32.6 cSt). Short-term engine tests have been carried out on this fuel.

## References

1. Knothe, G., Dunn, R.O., and Bagby, M.O. (1977) Biodiesel: The Use of Vegetable Oils and Their Derivatives as Alternative Diesel Fuels, in *Fuels and Chemicals from Biomass*, B.C. Saha, and J. Woodward, editors, Am. Chem. Soc. Symp. Series, no. 666, ACS, Washington, DC, pp. 178–208.
2. Pryde, E.H. Vegetable Oils as Diesel Fuels: Overview (1983) *J. Am. Oil Chem. Soc.* 60, 1557.
3. Goering, C.E., Schwab, A.W., Daugherty, M.J., Pryde, E.H., and Heakin, A.J. Fuel Properties of Eleven Vegetable Oils (1982) *Trans. ASAE* 25, 1472–1483.
4. Bagby, M.O., Freedman, B., and Schwab, A.W. Seed Oils for Diesel Fuels: Sources and Properties (1987) American Society of Agricultural Engineers Winter Meeting, Chicago, Illinois, Paper No. 87-1583.
5. Freedman, B., and Bagby, M.O. Heats of Combustion of Fatty Esters and Triglycerides (1989) *J. Am. Oil Chem. Soc.* 66, 1601–1605.
6. Freedman, B., M.O. Bagby, and H. Khoury. Correlation of Heats of Combustion with Empirical Formulas for Fatty Alcohols (1989) *J. Am. Oil Chem. Soc.* 66, 595–596.

**Table 3**  
Low-Temperature Properties of Alkyl Esters of Triglycerides

Substrate	Alkyl Ester	LTFT (°C)		CFPP (°C)	
		Neat	Blend <sup>a</sup>	Neat	Blend
Tallow	Methyl (MT)	20	—	9	-8
	Ethyl (ET)	13	1	8	-10
	Propyl (PT)	18	15	7	-10
	Butyl (BT)	13	14	3	-12
	Isopropyl (IPT)	19	12	7	-8
	Isobutyl (IBT)	17	14	8	-13
	2-Butyl (2-BT)	12	15	4	-3
Soy	Methyl (MS)	2	-12	-3	-14
Soy/Tallow <sup>b</sup>	MS/MT	3	-10	0	-13
Grease (9% FFA)	Ethyl	9	-3	0	-12
	2-Butyl	9	-2	-4	-18
#2 Diesel Fuel		-14	—	-27	—

<sup>a</sup>Blend of alkyl ester in diesel fuel, 20:80 (v/v).

<sup>b</sup>80:20 (v/v) blend of methyl soyate: methyl tallowate.

7. Ryan, T.W., III, Dodge, L.G., and Callahan, T.J. The Effects of Vegetable Oil Properties on Injection and Combustion in Two Different Diesel Engines (1984) *J. Am. Oil Chem. Soc.* 61, 1610–1619.
8. Ryan, T.W., III, and Bagby, M.O. (1993) in *New Developments in Alternative Fuels and Gasolines for SI and CI Engines*, Society of Automotive Engineers, Publication SP-958.
9. Freedman, B., and Bagby, M.O. Predicting Cetane Numbers of n-Alcohols and Methyl Esters from Their Physical Properties (1990) *J. Am. Oil Chem. Soc.* 67, 565–571.
10. Knothe, G., Bagby, M.O., Ryan, T.W., III, and Callahan, T.J. Degradation of Unsaturated Triglycerides Injected into a Pressurized Reactor (1991) *J. Am. Oil Chem. Soc.* 68, 259–267.
11. Knothe, G., Bagby, M.O., Ryan, T.W., III, Wheeler, H.G., and Callahan, T.J. Semi-Volatile and Volatile Compounds Formed by Degradation of Triglycerides in a Pressurized Reactor (1992) *J. Am. Oil Chem. Soc.* 69, 341–346.
12. Bruwer, J.J., Boshoff, B. Van D., Hugo, F.J.C., Fuls, J., Hawkins, C., vander Walt, A.N., and Engelbrecht, A. Sunflower Seed Oil as Extender for Diesel Fuel in Agricultural Tractors (1980) South African Institute for Agricultural Engineers Symposium.
13. Bruwer, J.J., Boshoff, B. Van D., Hugo, F.J.C., Fuls, J., Hawkins, C., vander Walt, A.N., Engelbrecht, A., and du Plessis, L.M. The Utilization of Sunflower Seed Oil as a Renewable Fuel for Diesel Engines (1980) American Society of Agricultural Engineers National Energy Symposium, Kansas City, Missouri.
14. Boruff, P., A.W. Schwab, C.E. Goering, and E.H. Pryde. Engine Evaluation of Diesel Fuel-Aqueous Ethanol Microemulsions (1980) American Society of Agricultural Engineers Winter Meeting, Chicago, Illinois, Paper No. 80-1523.
15. Dunn, R.O., and Bagby, M.O. Solubilization of Methanol and Triglycerides: Unsaturated Long-Chain Fatty Alcohol/Medium-Chain Alkanol Mixed Amphiphile Systems (1994) *J. Am. Oil Chem. Soc.* 71, 101–108.
16. Ziejewski, M., Kaufman, K.R., Schwab, A.W., and Pryde, E.H. Diesel Engine Evaluation of a Nonionic Sunflower Oil-Aqueous Ethanol Microemulsion (1984) *J. Am. Oil Chem. Soc.* 61, 1620–1626.
17. Goering, C.E., and Fry, B. Engine Durability Screening Test of a Diesel Oil/Soy Oil/Alcohol Microemulsion Fuel (1984) *J. Am. Oil Chem. Soc.* 61, 1627–1632.
18. Freedman, B., Pryde, E.H., and Mounts, T.L. Variables Affecting the Yields of Fatty Esters from Transesterified Vegetable Oils (1984) *J. Am. Oil Chem. Soc.* 61, 1638–1643.
19. Freedman, B., Butterfield, R.O., and Pryde, E.H. Transesterification Kinetics of Soybean Oil (1986) *J. Am. Oil Chem. Soc.* 63, 1375–1380.
20. Mittelbach, M. Lipase Catalyzed Alcoholysis of Sunflower Oil (1990) *J. Am. Oil Chem. Soc.* 67, 168–170.
21. Nelson, L.A., Foglia, T.A., and Marmer, W.N. Lipase-Catalyzed Production of Biodiesel (1996) *J. Am. Oil Chem. Soc.* 73, 1191–1195.
22. Mittelbach, M., and Trillhart, P. Diesel Fuels Derived from Vegetable Oils, III. Emission Test Using Methyl Esters of Used Frying Oil (1988) *J. Am. Oil Chem. Soc.* 65, 1185.
23. Freedman, B., Pryde, E.H., and Kwolek, W.F. Thin Layer Chromatography/Flame Ionization Analysis of Transesterified Vegetable Oils (1984) *J. Am. Oil Chem. Soc.* 61, 1215–1220.
24. Freedman, B., Kwolek, W.F., and Pryde, E.H. Quantitation in the Analysis of Transesterified Soybean Oil by Capillary Gas Chromatography (1986) *J. Am. Oil Chem. Soc.* 63, 1370–1375.
25. Plank, C., and Lorbeer, E. Simultaneous Determination of Glycerol and Mono-, Di- and Triglycerides in Vegetable Oil Methyl Esters by Capillary Gas Chromatography (1995) *J. Chromatogr. A* 697, 461–468.
26. Foglia, T.A. and Jones, K.C. Quantitation of Neutral Lipid Mixtures Using High Performance Liquid Chromatography with Light Scattering Detection, (1997) *J. Liq. Chrom. and Rel. Technol.*, 20: 1829–1838.
27. Owen, K., and Coley, T. (1990) *Automotive Fuels Handbook*, Society of Automotive Engineers, Warrendale, Pennsylvania, pp. 353–403.
28. Dunn, R.O., and Bagby, M.O. Low-Temperature Properties of Triglyceride-Based Diesel Fuels: Transesterified Methyl Esters and Petroleum Middle Distillate/Ester Blends (1995) *J. Am. Oil Chem. Soc.* 72, 895–904.
29. Lee, I., Johnson, L.A., and Hammond, E.G. Use of Branched-Chain Esters to Reduce the Crystallization Temperature of Biodiesel (1995) *J. Am. Oil Chem. Soc.* 72, 1155–1160.
30. Foglia, T.A., Nelson, L.A., Dunn, R.O., and Marmer, W.N. Low-Temperature Properties of Alkyl Esters of Tallow and Grease. (1997) *J. Am. Oil Chem. Soc.*, 74: 951–955.
31. Clark, S.J., Wagner, L., Schrock, M.D., and Piennaar, P.G. Methyl and Ethyl Soybean Esters as Renewable Fuels for Diesel Engines (1984) *J. Am. Oil Chem. Soc.* 61, 1632–1638.
32. Schwab, A.W., Bagby, M.O., and Freedman, B. Preparation and Properties of Diesel Fuels from Vegetable Oils (1987) *Fuel* 66, 1372–1378.
33. Schwab, A.W., Dykstra, G.J., Selke, E., Sorenson, S.C., and Pryde, E.H. Diesel Fuel from Thermal Decomposition of Soybean Oil (1988) *J. Am. Oil Chem. Soc.* 65, 1781–1786.