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INVESTIGATION OF BIODIESEL CHEMISTRY, CARBON FOOTPRINT AND REGIONAL FUEL QUALITY

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FINAL REPORT

Investigation of Biodiesel Chemistry, Carbon Footprint and Regional Fuel Quality

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EXECUTIVE SUMMARY

The AVFL-17a Project was undertaken by CRC as a follow-up to the previous AVFL-17 Project, which provided a state-of-knowledge assessment of biodistillates (both biodiesel and renewable diesel) as blendstocks for transportation fuels. Topics investigated in the earlier study included policy drivers, fuel volumes and feedstocks, production technologies, fuel properties and specifications, in-use handling and performance, emissions impacts, and life-cycle impacts. A subset of these issues was further investigated in this updated study, which focused on three areas:

1. Relationships between the chemical composition of biodiesel and fuel properties, performance, and emissions.

2. Greenhouse gas (GHG) emissions and life-cycle GHG impacts of specific biodiesel scenarios as compared to petroleum diesel.

3. Fuel specifications pertaining to biodiesel fuel in various countries, and issues related to in-use fuel quality.

The main findings and conclusions from this study are summarized below:

1.   Biodiesel Composition

Biodiesel fuel can be produced by transesterification of virtually any triglyceride feedstock. At present, the dominant feedstocks are soybean oil in the U.S., rapeseed oil in Europe, and palm oil in Southeast Asia. Animal fats (especially beef tallow) and used cooking oil (also called yellow grease) represent significant niche markets for biodiesel in many locations. Other vegetable oils of commercial interest as biodiesel feedstocks include camelina, canola, coconut, corn, jatropha, safflower, and sunflower. In addition, there is great interest in developing and utilizing algal lipids as biodiesel feedstocks.

Although biodiesel fuel produced from transesterification of triglycerides contains numerous individual fatty acid methyl ester (FAME) species, a particular fuel is generally dominated by only a few species. The five dominant fatty acids (FA) most commonly seen in biodiesel from vegetable oils and animal fats are palmitic (16:0), stearic (18:0), oleic (18:1), linoleic (18:2), and linolenic (18:3). Some algal-derived lipids are also dominated by these same fatty acid groups, while other algae are more diverse in their composition. Although available data are rather sparse, it appears that many algal lipids contain significant levels of polyunsaturated compounds – including species with 3-6 double bonds per molecule.

Detailed compositional profiles of biodiesel provide useful insights into similarities and differences among the various fuel types. Most of the 12 biodiesel compositions investigated in this study are dominated by C_{18} compounds, while a few have substantial amounts of lighter compounds; especially C_{12} for coconut and C_{16} for palm. Of the fuels dominated by C_{18}, the relative amounts of saturated (18:0), mono-unsaturated (18:1) and di-unsaturated (18:2) compounds vary considerably. Rapeseed and canola (a close relative of rapeseed) contain mostly 18:1; corn, safflower, soy, and sunflower contain mostly 18:2; jatropha, and yellow grease have more nearly equal amounts of 18:1 and 18:2.

2.   Biodiesel Properties

Physical and chemical properties of biodiesel are determined by their FAME compositional profiles. Due to variations in these profiles, biodiesel properties also vary substantially from one feedstock to the next. The properties of greatest interest are those defined by standard specifications that have been established for biodiesel – especially ASTM D6751 in the U.S. and EN 14214 in Europe. These properties include

sulfur content, kinematic viscosity, density, flash point, cetane number, iodine value, heating value, and low temperature operability metrics [cloud point (CP), pour point (PP), and cold filter plugging point (CFPP)]. Additional FAME properties are of importance with respect to in-use fuel quality, but are dictated primarily by biodiesel manufacturing, purification, and storage processes, rather than by the FA compositional profiles of the FAME. These properties include oxidation stability, water and sediment content, methanol content, ash, metals, acid number, glycerine content, and cold soak filterability.

Two other "properties" of biodiesel were calculated based upon the average compositional profiles of the FAME types derived from vegetable oils and animal fats: (1) average chain length and (2) average degree of unsaturation. Most biodiesels have average chain length of 17-19 carbons per molecule and average degree of unsaturation of 0.5-1.8 double bonds per molecule. Average unsaturation is highly correlated with several other fuel properties – including viscosity, specific gravity, iodine value, CP, PP, and CFPP.

Some biodiesel properties are largely explainable based upon the FA profiles of the materials. For example, cetane number is higher for FAMEs having high saturates content – such as coconut, palm, and tallow – and lower for FAMEs having high unsaturates content – such as camelina, safflower, soy, and sunflower. Similarly, iodine values are high for the highly unsaturated FAMEs, and low for the highly saturated FAMEs. The three low temperature properties (CP, PP, and CFPP) are very strongly inter-correlated. With all three metrics, highly saturated FAME give poor low temperature performance.

With pure FAME materials, average chain length has been shown to correlate with other fuel properties, such as cetane number, heating value, and low temperature performance. However, in a complex mixture of biodiesel, the effects of average chain length are not very noticeable. This is because the average chain length metric does not distinguish between saturated and unsaturated FAME groups. For many properties, the strong effect of unsaturation masks the weaker effect of chain length.

Low temperature operability is among the most important considerations for users of biodiesel. Poor cold flow properties result largely from the presence of long-chain, saturated fatty acid esters present in biodiesel. In general, the longer the carbon chain, the poorer the low temperature operability.

A different low temperature operability problem has been recognized recently, resulting from the formation of insoluble particles upon storage at cool temperatures. These insolubles arise from precipitation of trace-level non-FAME impurities, not from the major FAME components themselves. Because of these problems, ASTM has adopted a new Cold Soak Filterability test within the biodiesel standard, D6751. The two major families of impurities identified as causing such precipitate problems are saturated mono-glycerides and sterol glucosides.

Oxidative stability is another critical property with respect to in-use performance of biodiesel. Oxidative stability is related to the degree of unsaturation, with higher unsaturation (particularly poly-unsaturation) leading to poorer stability. Common vegetable oil feedstocks that produce fuels having over 50% polyunsaturated FAME include camelina, corn, safflower, soy, and sunflower; thus, these would be expected to have somewhat poorer inherent oxidative stability as compared to canola, coconut, jatropha, palm, and rapeseed.

Changes in a single compositional feature (such as chain length, chain branching, unsaturation, etc.) generally produces both desirable and undesirable changes in FAME properties. For example, factors that favor good oxidative stability (high saturation, low unsaturation) lead to poor low temperature operability. Due to the conflicting impacts of these FAME compositional features upon fuel properties, it is not possible to define a specific FAME composition that is optimum for all important fuel properties.

3.   Emissions Impacts of Biodiesel

From previous experimental work, use of biodiesel has been shown to provide significant emissions reduction benefits for three criteria pollutants: HC, CO, and PM, while the impacts on NOx emissions are smaller and more difficult to discern. In this study, a comprehensive database of engine/vehicle emissions results was compiled and evaluated. In large part, this assessment confirmed the earlier emissions findings – particularly in heavy-duty engine applications.

Particular emphasis was placed on B20 blends of biodiesel, as this is the most commonly used blending ratio, and is the maximum allowed under ASTM D7467. For B20 blends, the effects of biodiesel type (soy, rapeseed, palm, etc.) upon criteria emissions were investigated, as well as the effects of base fuel type (ULSD, CARB, and No. 2 DF), the effects of engine technology (NOx certification levels), and the effects of test cycle. Although slight differences are seen from case-to-case, the high degree of variability makes it difficult to discern clear effects for any of these factors.

The impacts of biodiesel upon non-criteria emissions show even greater variability. Numerous experimental studies have investigated aldehyde emissions, but the results are unclear and inconsistent, with approximately equal numbers of papers reporting increases and decreases in aldehyde emissions with use of biodiesel. In most cases, total aldehydes are dominated by formaldehyde and acetaldehyde, though acrolein and others are sometimes reported as being significant.

The effects of biodiesel usage upon NOx emissions are not consistent across all engine types and operating conditions. Although use of biodiesel is usually observed to increase NOx emissions, this is not universally true. NOx results vary depending upon numerous factors – including engine type and configuration, duty cycle, fuel injection strategy, emissions control strategy, and other factors. A number of theories have been developed to help understand these factors, and help explain the predominance of test data showing increased NOx with use of biodiesel.

It is now generally understood that the biodiesel NOx effect results from a combination of engine control mechanisms and fuel/combustion mechanisms. Depending upon specific operating conditions, these different mechanisms can either reinforce or cancel one another. No single mechanism or fuel property can fully explain the biodiesel NOx effect. The controlling mechanism(s) often appear to be different between high and low engine load conditions. Despite the small and variable effects of biodiesel on NOx emissions, a consensus has developed regarding certain fuel properties that are responsible for these effects. It is generally accepted that NOx emissions increase with increasing unsaturation, but decrease with increasing chain length.

Numerous mitigation approaches involving engine modifications and fuel modifications have been explored to reduce the NOx effect. Common engine modifications include retarded injection timing, phased injection, and use of EGR. Fuel modifications include reduction of the base fuel's aromatic content, addition of cetane improvers, use of anti-oxidants, and addition of blendstocks that are inherently low NOx emitting – such as Fischer-Tropsch (F-T) fuels or renewable diesel. The reported effectiveness of these approaches varies considerably throughout the literature. There is some indication that these measures will become less effective with newer engine technologies that already meet very low NOx emissions requirements. The long-term effects of biodiesel upon emission control systems in modern engines are not yet fully understood.

4. Life-Cycle Assessments

Life-cycle assessments (LCA) are increasingly being used to support regulations and policy that promote sustainable use of renewable fuels. To accurately estimate the life-cycle carbon intensity (CI) value for a biodiesel fuel scenario requires extensive data on all inputs, products, and emissions from each life-cycle stage. Numerous modeling tools and databases have been constructed to support fuel LCA. The GREET model, developed by Argonne National Laboratory, is one of the most popular models, and has been adopted by EPA for their Renewable Fuel Standard (RFS2) assessments. CARB has modified the GREET model with data specific to California, and has used the resulting CA-GREET model in support of its Low Carbon Fuel Standard (LCFS) regulations.

The effects of land use change (LUC) – and particularly indirect LUC (ILUC) – have been the focus of much debate. LCA models that include ILUC are complex, requiring inputs from economic models that generate feedback loops to reflect how changes in supply and demand affect price elasticity and co-product markets. These models produce high levels of uncertainty in the results, and include concerns about overlapping boundaries and double-counting of emissions. Two other factors that critically affect the final carbon intensity results from LCAs are: (1) the assumptions used for nitrous oxide (N_2O) emissions and (2) the allocation method used to attribute some GHG emissions to co-products.

Through review of the literature, a database of over 40 LCA studies and associated CI results was constructed. The primary CI functional unit used in this database is g $CO_{2\,eq}$/MJ_{fuel} – for both biodiesel and base petroleum diesel. In nearly all cases, the reference petroleum diesel fuel gave a CI value of 80-100 g CO_{2eq}/MJ_{fuel}, while the biodiesel cases fell between 20 and 60 g $CO_{2\,eq}$/$MJ_{fuel.}$ Although results varied considerably from case-to-case, it appears that a CI benefit of approximately 50-60% results from biodistillates produced from virgin vegetable oil feedstocks, and a slightly larger benefit results from use of waste feedstocks.

Despite the importance of ILUC effects, very few LCA studies conducted to-date have included consideration of these effects. Two that have included ILUC were conducted by CARB and EPA. In both cases, inclusion of ILUC dramatically increased the overall CI values of soy-derived biodiesel fuels – from 21 to 83 g $CO_{2\,eq}$/MJ_{fuel} in the CARB case; from 8 to 40 g $CO_{2\,eq}$/MJ_{fuel} in the EPA case.

5. Regional Fuel Specifications and Quality

Many countries have now adopted standard specifications for biodiesel fuel (B100). Most of these standards are patterned after those established in the U.S. (ASTM D6751) and Europe (EN 14214). These standards are constantly evolving to address new concerns about fuel quality and performance, and to accommodate introduction of improved analytical test methods.

Surveys of in-use biodiesel fuel quality have been conducted in the past, and have revealed some concerns about blending accuracy and adherence to fuel specifications. More recent surveys have shown improvement in fuel quality. It may be advisable to conduct additional in-use fuel quality surveys in the future, since significant changes in fuel specifications (i.e. addition of Rancimat oxidative stability test and low temperature filtration test) and QA/QC practices (expansion of the BQ-9000 Process) have occurred recently.

TECHNICAL SUMMARY

1.   Introduction

Interest in biodiesel is continuing to increase in the U.S. and throughout the world. This is motivated primarily by: (1) concerns about greenhouse gas (GHG) emissions and global climate change, (2) a desire for renewable/sustainable energy sources, and (3) an interest in developing domestic and more secure fuel supplies. With the technical and legislative landscapes of biodiesel being in a state of rapid flux, CRC recently sponsored Project AVFL-17 to define the state-of-knowledge regarding biodistillates as blendstocks for transportation fuels. Utilizing an extensive literature review, numerous biodistillate topics were investigated, including the following:

- policy drivers
- fuel volumes and feedstocks
- production technologies
- fuel properties and specifications
- in-use handling and performance
- emissions impacts
- life-cycle analyses

In this updated review of the biodistillate literature, three specific categories of biodiesel issues were the focus of study:

1. Relationships between the chemical composition of biodiesel and its properties, performance, and emissions. The impacts of different biodiesel feedstocks are of interest, such as soy, rapeseed, jatropha, etc. Also important are the impacts of the base diesel fuel into which biodiesel is blended, and impacts of the engine technology and operating conditions being used.

2. Greenhouse gas (GHG) emissions and the life-cycle GHG impacts of specific biodiesel scenarios as compared to petroleum diesel. Life-cycle assessments (LCA) of renewable diesel (produced by catalytic hydrogenation of the same biodiesel feedstocks) are also of interest.

3. Fuel specifications pertaining to biodiesel fuel in various countries, and issues related to in-use fuel quality.

For the purposes of this study, investigation into biodiesel was limited to on-road transportation fuel applications, thus excluding other possible uses such as heating fuels and aviation fuels. Because of its common usage, the greatest emphasis was placed on fatty acid methyl esters (FAME), although other forms of biodiesel were considered when appropriate. Also, when addressing GHG life-cycle issues, both biodiesel and renewable diesel scenarios were included. While use of neat biodiesel is of some interest, blends of biodiesel with petroleum diesel are much more commonly used. This study focused on biodiesel blends with low sulfur diesel (LSD), and especially ultra-low sulfur diesel (ULSD) fuels.

2.   Biodiesel Composition

Biodiesel fuel can be produced by transesterification of virtually any triglyceride feedstock. This includes oil-bearing crops, animal fats, and algal lipids. The literature contains hundreds of references of biodiesel production from a wide variety of feedstocks. At present, the dominant feedstocks are soybean oil in the U.S., rapeseed oil in Europe, and palm oil in Southeast Asia. Animal fats (especially beef tallow) and used cooking oil (also called yellow grease) represent significant niche markets for biodiesel in many locations. Other vegetable oils having real or potential commercial interest as biodiesel feedstocks include

camelina, canola, coconut, corn, jatropha, safflower, and sunflower. In addition, there is great interest in developing and utilizing algal lipids as biodiesel feedstocks.

Although biodiesel fuel produced from transesterification of triglycerides contains numerous individual FAME species, a particular fuel is generally dominated by only a few species. A list of the five dominant fatty acids (FA) most commonly seen in biodiesel from vegetable oils and animal fats is provided below in Table TS-1. Some algal-derived lipids are also dominated by these same fatty acid groups, while other algae are more diverse in their composition, containing significant amounts of several other FA groups.

Table TS-1. Dominant Fatty Acid (FA) Groups Found in Biodiesel

Common Name	Formal Name	CAS. No.	Abbreviation	Molecular Formula	Molecular Weight	Molecular Structure
Palmitic Acid	Hexadecanoic Acid	57-10-3	16:0	$C_{16}H_{32}O_2$	256.43	
Stearic Acid	Octadecanoic Acid	57-11-4	18:0	$C_{18}H_{36}O_2$	284.48	
Oleic Acid	cis-9-Octadecenoic Acid	112-80-1	18:1	$C_{18}H_{34}O_2$	282.47	
Linoleic Acid	cis-9,12-Octadecadienoic Acid	60-33-3	18:2	$C_{18}H_{32}O_2$	280.46	
Linolenic Acid	cis-9,12,15-Octadecatrienoic Acid	463-40-1	18:3	$C_{18}H_{30}O_2$	278.44	

In this report, 12 common fat and oil materials were considered as biodiesel feedstocks: camelina, canola, coconut, corn, jatropha, palm, rapeseed, safflower, soy, sunflower, tallow, and yellow grease. Based upon review of literature data, average compositional profiles of all 12 were determined. Examples of these profiles are shown below in Figure TS-1 for four common feedstocks: camelina, rapeseed, soy, and yellow grease.

Such profile depictions provide useful insights into similarities and differences among the various biodiesel types. For example, most of the 12 compositions are dominated by C_{18} compounds, while a few have substantial amounts of lighter compounds; especially C_{12} for coconut and C_{16} for palm. Of the fuels dominated by C_{18}, the relative amounts of saturated (18:0), mono-unsaturated (18:1) and di-unsaturated (18:2) compounds vary considerably. Rapeseed and canola (a close relative of rapeseed) contain mostly 18:1; corn, safflower, soy, and sunflower contain mostly 18:2; jatropha, and yellow grease have more nearly equal amounts of 18:1 and 18:2. Of the 12 fats and oils investigated here, camelina contains the highest level of 18:3.

Despite great interest in algal feedstocks for biodiesel, the literature contains relatively few reports of detailed compositional profiles of the triglyceride fractions in algal lipids. It is known that for some algal strains, the FA compositional profiles are highly influenced by specific growth conditions such as nutrient levels, temperatures, and light intensities. This makes it more difficult to define a single compositional profile for algal-based biodiesel, as compared to vegetable oil-based biodiesel. Also, although many different algal materials have been investigated, the exact species is often unknown, or mixed species are used. In addition, there are relatively few instances of the same algal species being characterized by more than one research group.

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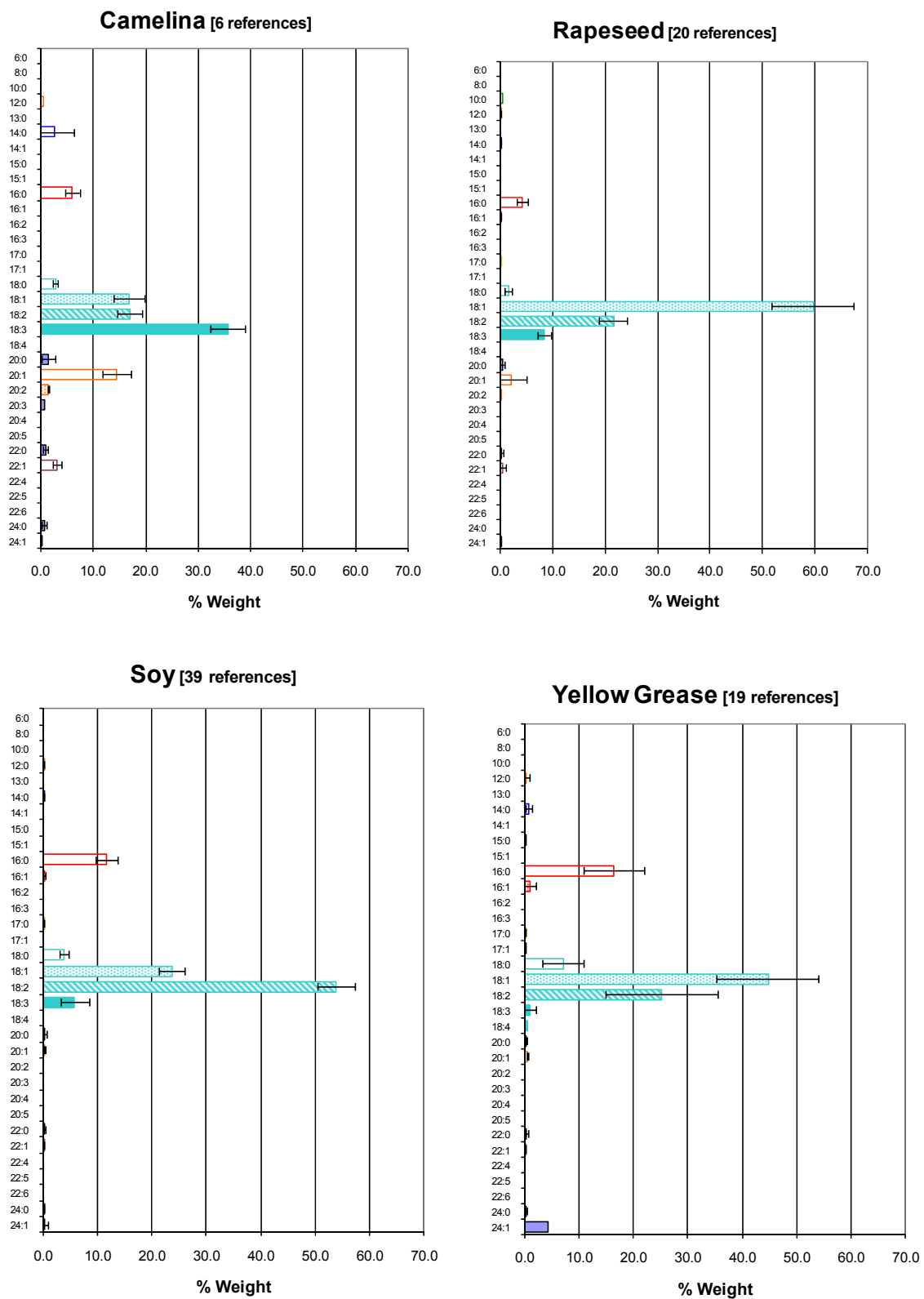
Figure TS-1. Compositional Profiles of Biodiesel from Fats and Oils
(Confidence intervals represent one standard deviation)

Most algae that have been investigated as potential biodiesel feedstocks are green algae (Chlorophyceae), although several other types have also been reported, including cyanobacteria, yellow-green algae, golden algae, red algae, and others. Triacylglycerides are the desired component within algal lipids for use as biodiesel feedstocks. However, these lipids typically also contain lesser amounts of wax esters, sterols, tocopherols, hydrocarbons, and other compounds. Just as with the vegetable oils, triglyceride production within algae varies considerably from one species to the next. For algae, this is typically represented as the total lipid content, expressed as mass percent on a dry basis. Lipid contents vary widely, from less than 10% to over 50%. Lipid content alone does not define the total productivity of an algal strain, as productivity is the product of lipid content and algal growth rates.

Average lipid fatty acid (FA) profiles were determined for 12 algal species reported in the literature. The amount and quality of algal compositional data are much less than the vegetable oil compositional data; thus, creating considerable uncertainty in the algal profiles. Nevertheless, it is clear that the FA compositions vary greatly across the range of algae investigated. Also, although most of these algal lipids have considerable amounts of C_{16} and C_{18} fatty acids, they are not as dominated by these species as are most vegetable oils. Furthermore, some algal FA profiles are broader than those of vegetable oils, containing significant amounts of both lighter species (C_{12}-C_{14}) and heavier species (C_{20}-C_{22}). Finally, many of the algal profiles contain substantial amounts of highly unsaturated species, including FAs with 3-6 double bonds. This raises concerns with respect to oxidative stability. Profiles of two common algal strains (*Chlorella vulgaris* and *Chromonas salvina*) are shown in Figure TS-2.
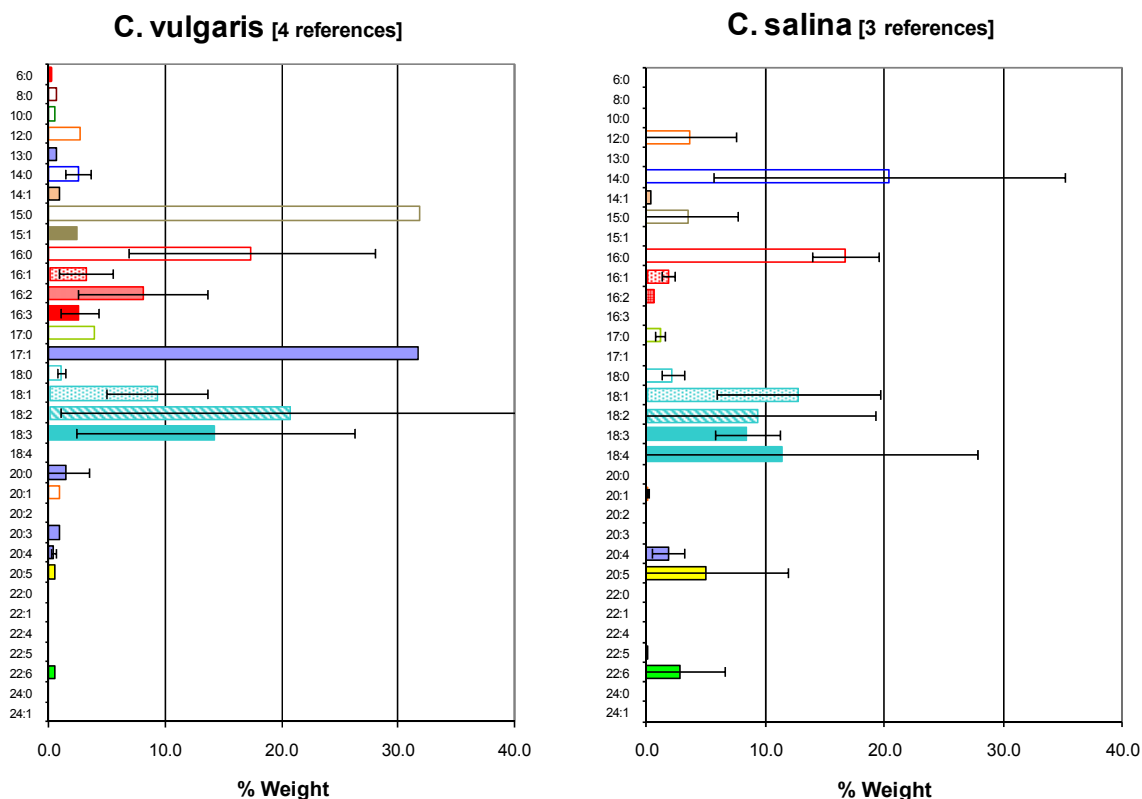
Figure TS-2. Fatty Acid Compositional Profiles of Algal Lipids
(Confidence intervals represent one standard deviation)

3.   Biodiesel Properties

Physical and chemical properties of biodiesel are determined by their FAME compositional profiles. Due to variations in these profiles, biodiesel properties also vary substantially from one feedstock to the next. The properties of greatest interest are those defined by standard specifications that have been established for biodiesel – especially ASTM D6751 in the U.S. and EN 14214 in Europe. These properties include sulfur content, kinematic viscosity, density, flash point, cetane number, iodine value, heating value, and low temperature operability metrics [cloud point (CP), pour point (PP), and cold filter plugging point (CFPP)]. Additional FAME properties are of importance with respect to in-use fuel quality, but are dictated primarily by biodiesel manufacturing, purification, and storage processes, rather than by the FA compositional profiles themselves. These properties include oxidation stability, water and sediment content, methanol content, ash, metals, acid number, glycerine content, and cold soak filterability.

Two other "properties" of biodiesel were calculated based upon average compositional profiles of the 12 FAME types derived from vegetable oils and animal fats: (1) average chain length and (2) average degree of unsaturation. Average chain length was computed by multiplying the mass fraction of each FA constituent times its associated carbon number, then summing over the entire profile. (Most biodiesels have an average chain length of 17-19 carbons per molecule.) Similarly, average degree of unsaturation was computed by multiplying the mass fraction of each FA constituent times the associated number of carbon-carbon double bonds, then summing over the entire profile. (Most biodiesels have an average degree of unsaturation between 0.5 and 1.8 double bonds per molecule.)

3.1   Properties of Biodiesel from Fats and Oils

Based upon review of literature data, average properties for the 12 vegetable oil and animal fat derived biodiesels were determined. (At the present time, there is insufficient data to determine similar average properties for algal-derived biodiesel.) Results were portrayed graphically, to allow for ready comparison among the 12 FAME materials. Examples of these graphs are given in Figure TS-3, which includes four properties that have considerable variation among the set of biodiesels: viscosity, cloud point, cetane number, and average degree of unsaturation.

In many cases, the range of properties shown for the 12 biodiesel materials is explainable based upon the FA profiles of the materials. For example, cetane number is higher for FAMEs having high saturates content – such as coconut, palm, and tallow – and lower for FAMEs having high unsaturates content – such as camelina, safflower, soy, and sunflower. Similarly, iodine values (not shown here) are high for the highly unsaturated FAMEs, and low for the highly saturated FAMEs. The three low temperature properties (CP, PP, and CFPP) are strongly inter-correlated. Thus, the PP and CFPP behaviors across the 12 FAME materials are very similar to the CP behavior shown in Figure TS-3. With all three metrics, the highly saturated FAMEs produced from palm and tallow give the poorest low temperature performance, while better performance is observed with the highly unsaturated FAMEs.

Of the 12 biodiesels produced from vegetable oils and animal fats, that derived from coconut oil is most different (furthest from the mean) with respect to several properties – including viscosity, flash point, iodine value, and heating value. This is a consequence of coconut's FA profile, which is dominated by low molecular weight, saturated FAME, particularly C12:0 (lauric acid) and C14:0 (myristic acid).
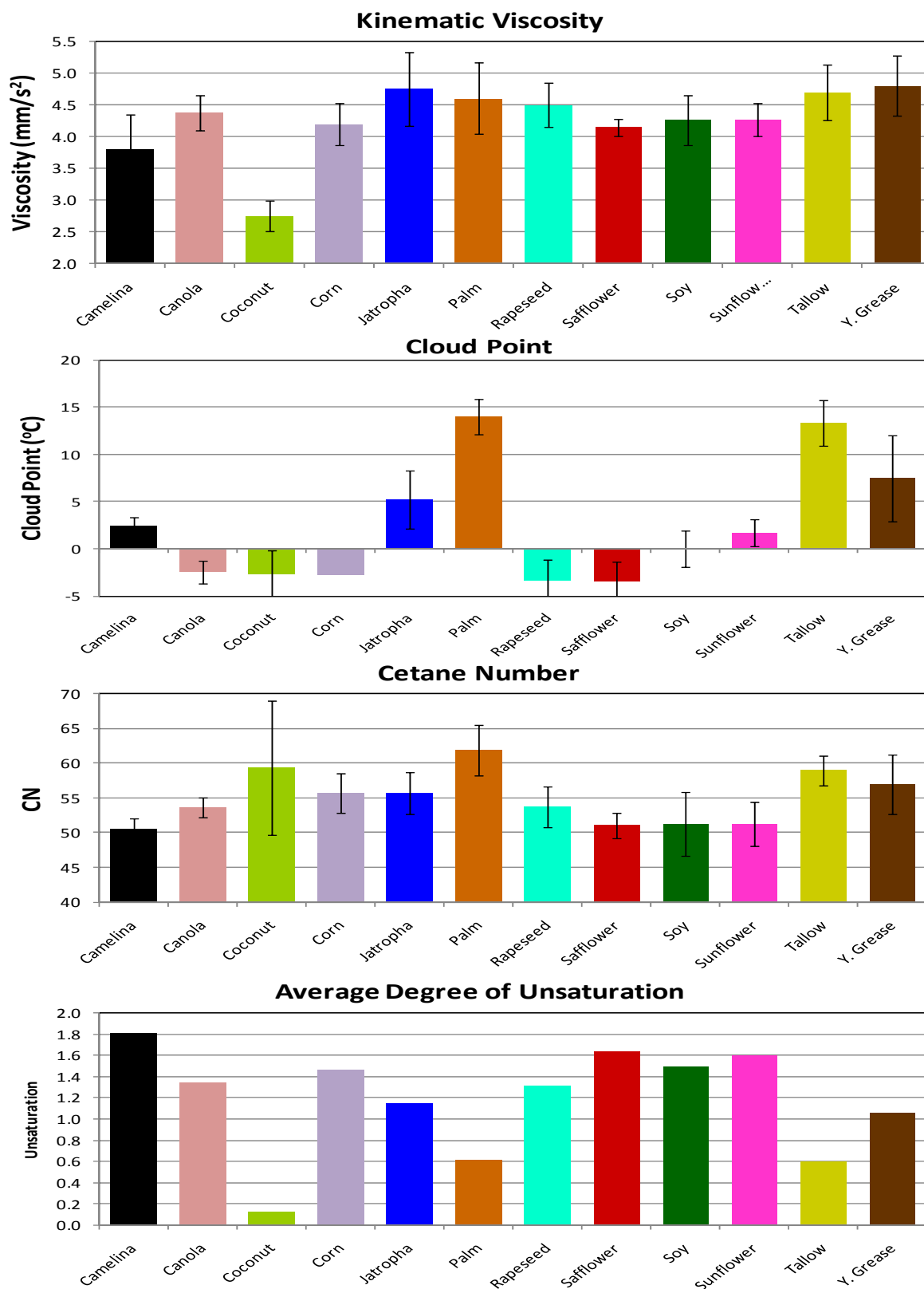
Figure TS-3. Average Physical/Chemical Properties of Biodiesel (FAME) from Fats and Oils
(Confidence intervals represent one standard deviation)

3.2   Relationships between Properties and Composition

The two compositional features of FAME generally regarded as most important in determining fuel properties are FA chain length and degree of unsaturation. Numerous researchers have investigated relationships between particular properties and compositional features by careful study of pure compounds, or mixtures of pure compounds. In this study, we compiled considerable information on both properties and compositions of complete FAME products from many feedstocks, enabling investigation of relationships across a range of realistic biodiesel types.

To explore these relationships more thoroughly, sets of correlation tables and graphical displays were produced. In particular, average properties determined for the 12 biodiesel types were plotted against average chain length, and against average degree of unsaturation. Examples of these relationships are provided in Figure TS-4, which shows six FAME properties (viscosity, specific gravity, cloud point, cetane number, iodine value, and higher heating value) plotted against the average degree of unsaturation. Least squares fits are also shown, although coconut was eliminated as an outlier in two cases: viscosity and cloud point. These analyses demonstrate that average degree of unsaturation is a good predictor of other FAME properties.

On the other hand, average chain length is not a good predictor of other properties. In part, the poor correlation between FAME properties and average chain length stems from the narrow range of chain lengths that describe most biodiesel materials. (Eleven of the 12 materials investigated here have average lengths between 17 and 19.) In addition, the definition of average chain length does not distinguish between saturated and unsaturated FAME groups. For many properties, the strong effect of unsaturation can mask the weaker effect of chain length. More sophisticated data analysis techniques would be required to properly determine the separate effects of multiple variables upon fuel property relationships.

Low temperature operability is among the most important considerations for users of biodiesel. Just as with conventional diesel fuel, precautions must be taken to ensure satisfactory low temperature operability of biodiesel and its blends. Poor cold flow properties result largely from the presence of long-chain, saturated fatty acid esters in biodiesel. Saturated methyl esters longer than C_{12} significantly increase CP and PP. In general, the longer the carbon chain, the higher the melting point, and poorer the low temperature performance. Feedstocks with highly saturated fatty acid structures (such as palm oil and tallow) produce biodiesel fuels with poor low temperature operability; whereas feedstocks with highly unsaturated fatty acid structures (such as rapeseed and safflower oil) produce fuels having better operability. Although the relationship between carbon chain length and low temperature properties is quite strong for pure FAME compounds, the effect appears more subtle when considering complex mixtures of FAME in actual biodiesel samples.

Recently, another low temperature operability problem has been recognized, resulting from formation of insoluble particles upon storage at cool temperatures. These insolubles arise from precipitation of trace-level non-FAME impurities, not from the major FAME components themselves. Because of these problems, ASTM has adopted a new Cold Soak Filterability test within the biodiesel standard, D6751. The two major families of impurities identified as causing such precipitate problems are saturated mono-glycerides and sterol glucosides.

Cetane number (CN) of biodiesel decreases sharply with an increasing degree of unsaturation. On the other hand, cetane index (CI) shows very poor correlation with CN, or with any other FAME property. Although CI is commonly reported in the literature (derived from equations meant for petroleum diesel), there is no accepted methodology for its determination in biodiesel. Consequently, reported CI values should not be regarded as accurate descriptors of FAME materials.
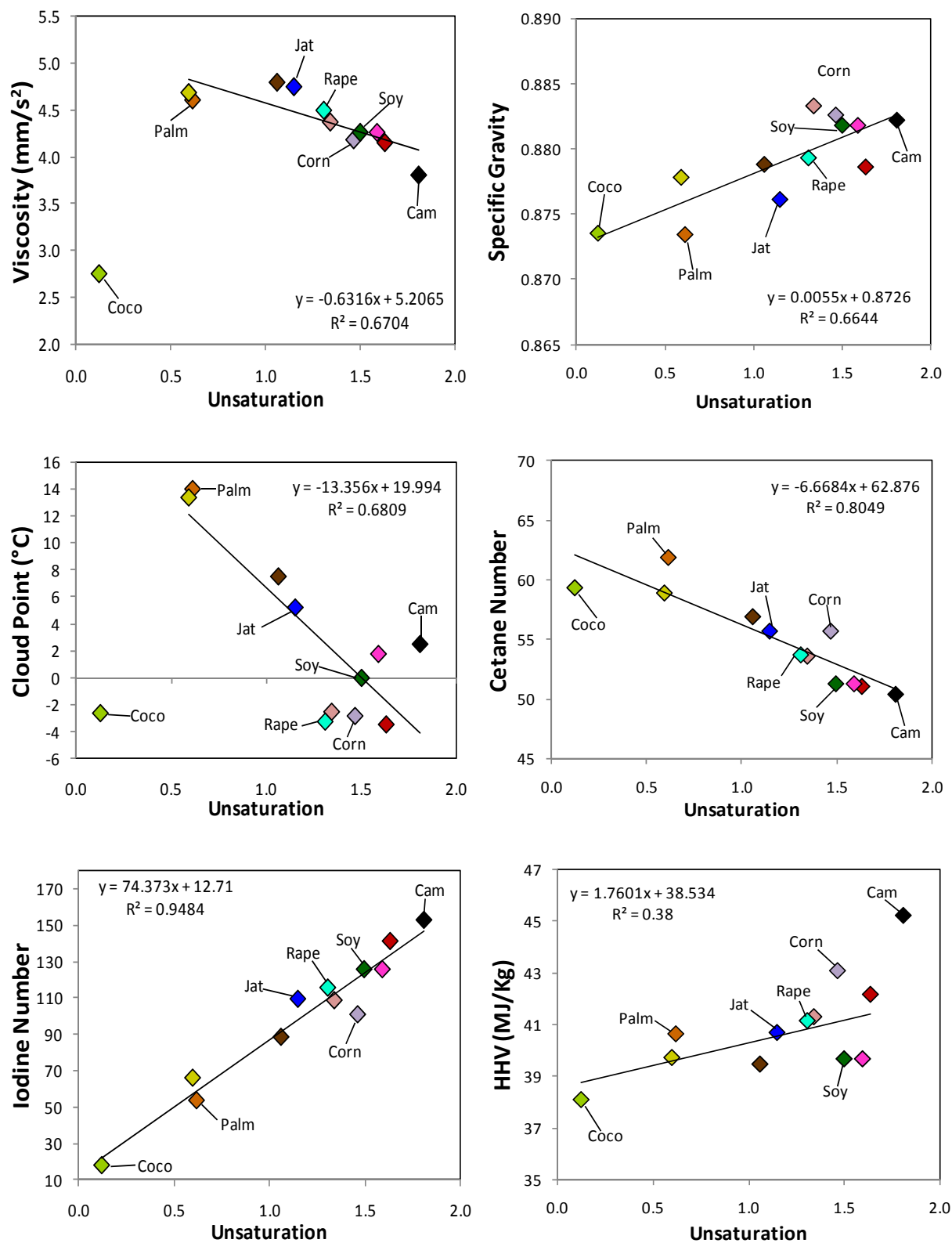
Figure TS-4. Relationships between Biodiesel Unsaturation and Other Fuel Properties
(Biodiesel feedstock abbreviations: "Coco" = coconut; "Jat" = Jatropha; "Cam" = camelina)

Of all the biodiesel properties investigated, iodine value (IV) has the strongest correlation with average degree of unsaturation. This is expected, since IV is a direct measure of unsaturation. IV was originally included as a specification in the European biodiesel standard, EN 14214, to ensure satisfactory oxidative stability of the fuel. However, IV is simply a measure of total unsaturation, whereas oxidative stability is more strongly influenced by the amount of FAME molecules having multiple double bonds.

Biodiesel from all feedstocks is generally regarded as having excellent lubricity, and the lubricity of ULSD can be improved by blending with biodiesel. 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. Some of the same impurities (such as monoglycerides) are responsible for poor low temperature operability problems. Efforts to reduce these impurities (to improve low temperature properties) could have the unintended consequence of worsening lubricity.

Oxidative stability is arguably the most important property with respect to in-use performance of biodiesel. Oxidative stability is related to unsaturation. In general, higher unsaturation leads to poorer stability. FAME molecules containing a carbon that is adjacent to two double bonds (a bis-allylic group) are particularly unstable. It is for this reason that the European biodiesel standard (EN 14214) includes a separate specification for linolenic acid methyl ester, which contains two bis-allylic groups.

The importance of polyunsaturated FAME (as opposed to monounsaturated FAME) with respect to fuel stability is now widely recognized. Common vegetable oil feedstocks that produce fuels having over 50% polyunsaturated FAME include camelina, corn, safflower, soy, and sunflower; thus, these would be expected to have somewhat poorer inherent oxidative stability as compared to canola, coconut, jatropha, palm, and rapeseed. Camelina-derived biodiesel is noteworthy, as it contains about 35% tri-unsaturated FAME. Consequently, camelina biodiesel may be expected to have especially poor oxidative stability.

Changes in a single compositional feature (such as chain length, chain branching, unsaturation, etc.) generally produce both desirable and undesirable changes in FAME properties. To a certain degree, this is unavoidable, as some properties are antagonistic. For example, compositional features that favor good oxidative stability (high saturation, low unsaturation) lead to poor low temperature performance. Table TS-2 summarizes the significant relationships between FAME composition and FAME properties, using arrows of different thickness and length to characterize the changes in FAME properties resulting from an increase in value of each compositional feature. Long arrows indicate relatively large effects, while shorter arrows indicate relatively small effects. Thick arrows indicate relationships that seem certain, based upon consistency of literature reports, while narrow arrows are less certain. The relationships shown in Table TS-2 represent the best judgment of this report's authors, based upon review of the literature, as well as some independent data analysis that is summarized in this report.

Due to the conflicting impacts of certain FAME compositional features upon fuel properties, it is not possible to define a specific FA composition that is optimum for all important biodiesel properties. However, useful formulation guidelines can be offered with respect to two important properties: low temperature performance and oxidative stability. For good low temperature performance, biodiesel should have a low level of FAME containing long-chain saturated FA, and a high level of FAME containing unsaturated FA. For good oxidative stability, biodiesel should contain high levels of FAME containing saturated and mono-unsaturated FA, but low levels of multi-unsaturated FA. (Biodiesel stability can also be improved by use of anti-oxidant additives. Although raw fats and oils usually contain natural anti-oxidants such as tocophereols and caratenoids, synthetic anti-oxidants have generally been found to be more effective.) Some have concluded that palmitoleic acid (16:1) and oleic acid (18:1) provide the best compromise between oxidative stability and cold flow, without excessive reduction of cetane number.

Table TS-2. Relationships between FAME Level/Composition and Fuel Properties

Arrows indicate change in FAME properties resulting from increases in compositional items*

FAME Composition \ FAME Properties	Viscosity	Density	CP, PP, CFPP	Cetane Number	Iodine Number	Heating Value, MJ/kg	Lubricity	Oxidative Stability
FAME Blend Level (from B0 to B20)	↑	↑	↑	↓↑	↑	↓	↑	↓
Average Chain Length	↑	-	↑	↑		↑		
Chain Branching			↓	↓				
Degree of Unsaturation	↓	↑	↓	↓	↑	↓	-	↓
Alcohol Length and Branching	↑		↓	-				

* Notes:

Length of arrow indicates relative magnitude of effect

Thickness of arrow indicates certainty/consistency of effect

Symbol "-" indicates highly uncertain, or conflicting information

Blank box indicates that no relevant information was found

Impact of FAME blend level on Cetane Number depends upon the base fuel's CN

4.   Emissions Impacts of Biodiesel

In previous work, use of biodiesel has been shown to provide significant emissions reduction benefits for three criteria pollutants: HC, CO, and PM. The impacts on NOx emissions are smaller and more difficult to discern. In this study, these criteria emissions impacts were re-investigated, using an expanded database that we believe to be more relevant and robust. In the previous AVFL-17 project, published emissions results from nearly all sources were included and weighted equally. In this study, a more restrictive set of criteria was used. These criteria were similar to those defined by EPA in their recent RFS2 Regulatory Impact Analysis, and include the following:

- Use of a complete vehicle or a multi-cylinder engine that is in commercial use. (Generally, only engines from 1987 or later were included for data analysis.)
- Use of standardized and well characterized test cycles.
- Use of biodiesel (FAME) produced from commercially available vegetable oils or animal fats.
- Use of experiments in which a petroleum base diesel fuel was tested along with a biodiesel fuel (or blends of biodiesel) under identical conditions.

Particular emphasis was placed on B20 blends of biodiesel, as this is the most commonly used blending ratio, and is the maximum allowed under ASTM D7467. For these B20 blends, the effects of biodiesel type upon criteria emissions were investigated, as well as the effects of base fuel type, engine technology, and test cycle.

Much less information is available regarding the impacts of biodiesel upon non-criteria emissions. However, the most relevant information with respect to aldehyde emissions, PM number and size distributions, and PAH emissions was compiled. In addition, the issue of biodiesel's NOx effect was

thoroughly investigated, including explanations for its occurrence, the impacts of fuel properties and engine conditions upon the NOx effect, and mitigation measures taken to reduce the effect.

A detailed table (Appendix VII) was constructed to identify all literature sources included in the emissions database -- along with summary information about the engines, fuels, and test cycles used in each case. The database itself is structured as a spreadsheet (provided in electronic form only), containing approximately 450 distinct emissions tests for different combinations of engines/vehicles, test cycles, biodiesel feedstocks, and after-treatment systems.

To assess the emissions impacts of biodiesel, literature-reported emissions values (in units of g/mi or g/bhp-hr) were computed as percent change compared to a reference petroleum diesel fuel. This approach helps to "normalize" the emissions results, and allows for clearer identification of fuel effects of specific biodiesel fuels and blends upon emissions. Most emissions impacts were evaluated for three subsets of the database: (1) heavy-duty (HD) and medium-duty (MD) engine dynamometer tests, (2) HD and MD chassis dynamometer tests, and (3) light-duty (LD) engine and chassis dynamometer tests.

4.1 Impacts of Biodiesel Blend Level

To assess the impacts of biodiesel blend level upon criteria emissions, a set of graphs was constructed in which the percent change in emissions (compared to base fuel) was plotted against B-level. (The term "B-level" is frequently used to indicate the concentration of biodiesel included in the final blend.) This type of graphical depiction has been commonly used by EPA and others to illustrate biodiesel's emissions impacts. Separate graphs were made for each criteria pollutant and engine/vehicle type. In this initial assessment, there was no differentiation among biodistillate feedstock type (i.e. soybean, rapeseed, palm, etc.), base fuel type, emissions test cycles, or engine model year. (These parameters were investigated later.) This inclusive approach was meant to show the wide range of emissions effects reported in the literature.

Most reported emissions tests were conducted using B20 and B100 blend levels, with relatively little data at other B-levels. The B20 and B100 emissions effects determined from these evaluations are summarized in Table TS-3, which shows individual effects for each pollutant and each engine/vehicle testing type. As expected, the HD/MD engine dyno results show clear emissions reductions for HC, CO, and PM when using biodiesel; while the NOx effects are much smaller, and show a slight increase. The HD/MD chassis dyno results are quite similar for HC and CO, while opposite trends with increasing B-level are seen for PM and NOx. The LD emissions effects are small and variable.

It should be emphasized that all these assessments include considerable variability; and that more sophisticated data analysis methods are required to determine the statistical significance of the results. However, of the three engine/vehicle testing types investigated here, the HD/MD engine dynamometer emissions set contains the most data and appears to be the most robust. An overall summary of the biodiesel emissions effects in this set is shown graphically in Figure TS-5, where it is compared with EPA's assessment from 2002. For NOx, results of the current study are nearly identical to EPA's. For HC and CO, results from the current study are similar to EPA's at the B20 level, but show smaller benefits at the B100 level. For PM, results from the current study show slightly greater emissions reductions than EPA at the B20 level, but slightly greater reductions at B100.

Table TS-3 Percent Change in Emissions using B20 and B100 (in 4-Cycle Engines)

Fuel	Pollutant	HD/MD Engine Dyno	HD/MD Chassis Dyno	LD Chassis Dyno
B20	HC	-17.4	-13.3	-7.6
	CO	-14.1	-17.3	+1.1
	PM	-17.2	-10.5	-1.7
	NOx	+1.8	-0.5	+3.8
B100	HC	-48.3	-59.5	-20.1
	CO	-34.3	-39.0	+14.9
	PM	-44.3	+3.8	+7.9
	NOx	+9.0	-4.9	+6.1

Figure TS-5. Emissions Effects of Biodiesel from HD Engine Dynamometer Tests

A numerical comparison of the B20 emissions effects determined from different studies is provided in Table TS-4, which shows that the effects determined from the current study fall within the range of effects reported in the earlier studies. In large part, all these studies utilized similar emissions databases, although the specific data selection criteria and statistical methods differed somewhat.

Table TS-4. Comparison of B20 Emissions Effects from HD Dynamometer Tests

(Percent change from base fuel)

Pollutant	EPA (2002)	McCormick et al. (2006)	AVFL-17 (2009)	This Study
HC	-21.1	-11.6	-21.2	-17.4
CO	-11.0	-17.1	-18.7	-14.1
PM	-10.1	-16.4	-24.1	-17.2
NOx	+2.0	+0.6	-0.6	+1.8

4.2   B20 Impacts on Criteria Emissions

With B20 being the most frequently tested blend of biodiesel, and also the highest concentration allowed by ASTM D7467, further analyses of the B20 results were performed to investigate the impact of biodiesel type, base fuel type, engine technology, and test cycle load. Figure TS-6 summarizes these results for the data subset consisting of HD/MD engine- and chassis-dyno tests. (At the B20 level, the emissions results from engine dyno and chassis dyno testing are quite similar. Combining these two gives a more robust dataset.) As illustrated in this figure, there is a high degree of variability in the results, indicating that statistically significant differences are unlikely. Nevertheless, some interesting directional trends are suggested.

In comparing the impacts of different biodiesel types, it appears that biodiesel from all feedstocks give substantial emissions reduction benefits for HC, CO, and PM; while the NOx effects are small and uncertain. The most highly saturated feedstock, palm, appears to give a small NOx benefit, while the HC, CO, and PM benefits from palm-derived biodiesel may be somewhat less than from the other feedstocks. Soy-based biodiesel – which dominates the entire dataset – shows a slight NOx increase at the B20 level.

To investigate whether the base fuel into which biodiesel is blended has a significant effect on the emissions impacts of B20, all tests in the database were categorized as having one of three base fuel types: ULSD, CARB Diesel, and No. 2 DF. The results shown in Figure TS-6 suggest that use of biodiesel in CARB base fuel may provide somewhat lesser HC and CO emissions benefits compared to No. 2 DF or ULSD base fuels. However, due to the high variability, definitive conclusions are not possible. Also, the quantities of data in each base fuel category are very different, with fewer than 20 points in the CARB set, and over 70 points in the No. 2 DF set.

Diesel engine technology has advanced greatly over the past two decades, driven in part by increasingly stringent emissions standards that have been applied. It is conceivable that as engine technology changes, the response to use of biodiesel also changes. To investigate this, the emissions database was sorted by engine model year, with certain time periods being lumped together to approximate changes in HD NOx standards. The four time periods selected are as follows:

- 1987 – 1990:   NOx $\geq$ 6 g/bhp-hr
- 1991 – 1997:   NOx = 5 g/bhp-hr
- 1998 – 2003:   NOx = 4 g/bhp-hr
- 2004 – Present: NOx $\leq$ 2.5 g/bhp-hr

The results shown in Figure TS-6 suggest that engine technology has little impact upon the B20 fuel effects, with a possible exception of increasing PM reductions with advanced technology. However, it should be mentioned that relatively few engines/vehicles are included in the oldest and newest categories.

The impacts of engine load were also investigated. Following the approach defined by EPA, dynamometer test cycles were categorized as having light, medium, or heavy load. The results shown in Figure TS-6 suggest that the heavy-load condition may increase NOx emissions. However, these results cannot be considered conclusive, due to the high overall variability, and the fact that a single test comprised the heavy load dataset.

4.3   Biodiesel Impacts on Non-Criteria Emissions

The issue of biodiesel's impacts on aldehyde emissions has been somewhat unclear and controversial. In a review of the literature conducted in 2008, Lapuerta, et al. identified approximately equal numbers of papers reporting increases and decreases in aldehyde emissions when using biodiesel. However, several

17
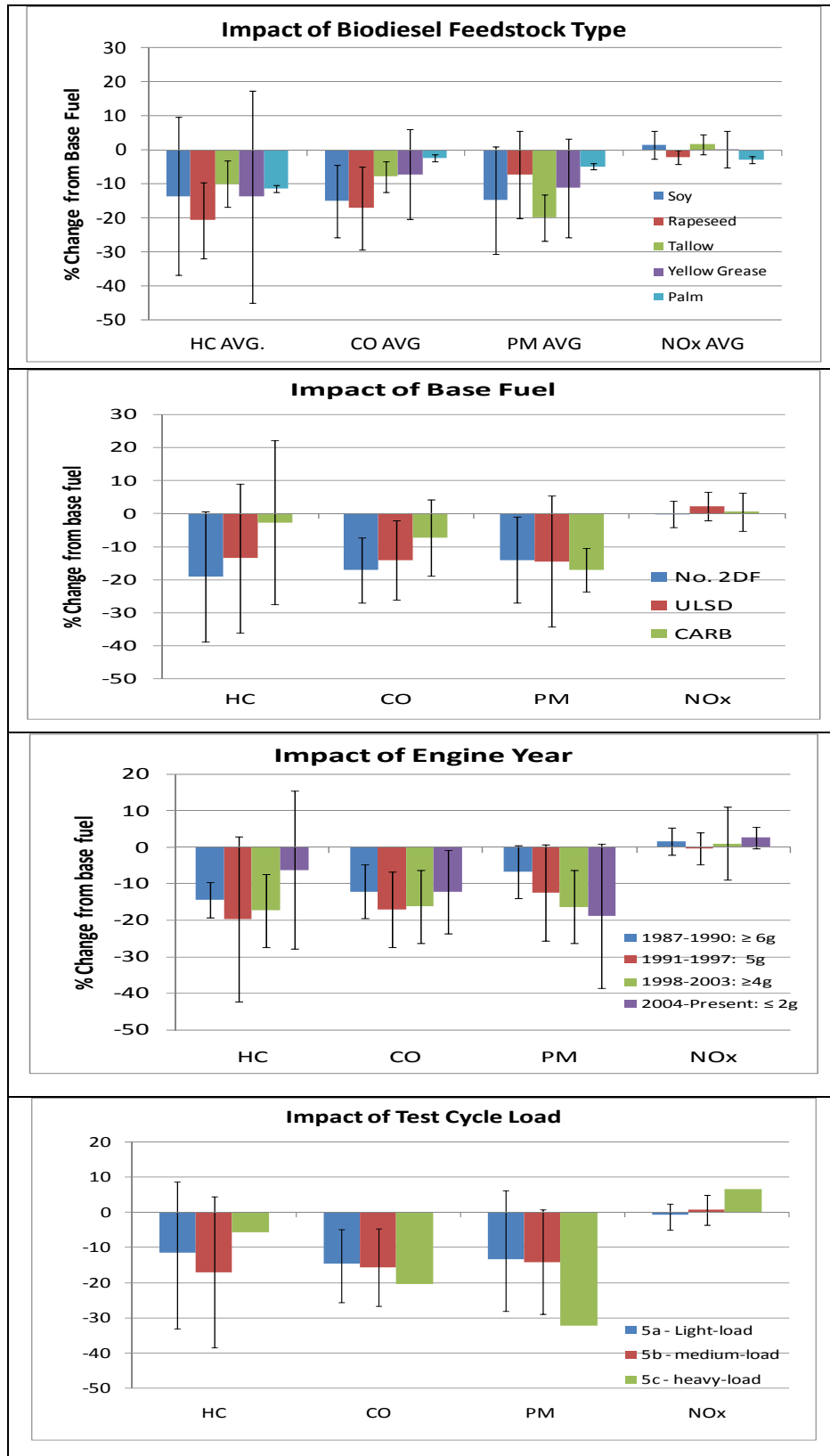
Figure TS-6. Impacts of B20 on Emissions from HD/MD Engine- and Chassis-Dyno Tests
(Error bars represent one standard deviation)

of the references cited used engines now regarded as obsolete, and fuels of questionable quality. The present study was limited to newer technology, multi-cylinder engines (generally 1991 and newer) and to biodiesel blends that were reasonably well characterized and originated from common feedstocks.

Aldehyde emissions were assessed using three engine/vehicle testing categories: (1) HD/MD engine dyno, (2) LD engine dyno, and (3) LD chassis dyno. The data analysis focused on three aldehydes: formaldehyde, acetaldehyde, and acrolein, but also included a category of total aldehydes, which was reported by many researchers. (In most cases, total aldehydes are dominated by formaldehyde and acetaldehyde.) Compared with the criteria emissions, aldehyde data are relatively sparse, and show even greater variability. While some data suggest that aldehydes from LD vehicles increase with use of biodiesel, the overall variability is so large that no firm conclusions can be made.

Although use of biodiesel provides a beneficial effect of reducing total PM emissions in most situations, there is growing interest in understanding how the number and size distributions of the PM may be affected. In particular, there is concern that while total particle mass may be reduced when using biodiesel, the number of small particles may increase. The term "nucleation mode particle" is used to define the very small particles (typically < 20 nm) arising from initial soot formation; exhausting of metallic compounds; and condensation of sulfuric acid, lube oil, and heavy unburned fuel constituents. (The terms "nanoparticle" and "nucleation particle" are sometimes used interchangeably.) The term "accumulation mode particle" refers to larger particles (typically 30-200 nm) arising from soot agglomeration and adsorption of organics onto the soot agglomerates. Generally, most ultrafine particle numbers are in the nucleation size range, while most ultrafine particle mass is in the accumulation size range.

Several excellent reviews on the topic of particulate emissions from diesel engines provide a good basis for understanding these issues with biodiesel emissions. Also, a number of biodiesel-specific studies have appeared recently. Taken together, these studies emphasize the importance of controlling sampling conditions to obtain meaningful particle size distributions. In well-controlled sampling studies, it appears that use of biodiesel reduces the number of accumulation mode particles under most operating conditions, and hence the total PM mass. However, several researchers have observed increases in the number of nucleation mode particles when using biodiesel. There is good evidence that these particles arise from condensation of unburned fuel or fuel impurities. It is expected that a diesel particulate trap would be highly effective in eliminating these nucleation mode particles.

With conventional diesel fuel, emissions of particulate PAH are of some concern. Several recent reports have appeared in which the PAH emissions from biodiesel and conventional diesel are compared. Based upon the limited information provided in these studies, it appears that use of biodiesel may provide a PAH reduction benefit compared to base fuel. However, the magnitude of these effects is quite small, and likely to be insignificant when using low concentration blends such as B20.

4.4   NOx Effects of Biodiesel

Of all the criteria emissions, NOx is the most difficult to understand and control. Use of biodiesel and biodiesel blends has a strong and consistent beneficial effect on emissions of HC, CO, and PM. However, for NOx, the effects are much smaller and variable. In diesel exhaust, NOx is predominantly composed of NO, with lesser amounts of NO_2. NOx formation mechanisms have been studied in some detail, and several literature references give good summaries of this area. In general, three formation processes are believed to be important: (1) thermal NOx, (2) prompt NOx, and (3) fuel NOx. Since the natural nitrogen levels in both diesel fuel and biodiesel are extremely low, the fuel NOx mechanism can be ignored.

Although use of biodiesel is usually observed to increase NOx emissions, this is not universally true. This is understandable, considering the complexity of the combustion process and the wide range of non-fuel

factors that influence emissions – such as air/fuel ratios, engine speed and load, fuel injection timing, and other parameters. The literature contains many reports of experimental studies in which use of biodiesel either reduced NOx emissions or had no impact. NOx emissions do not show a single, uniform response to the use of biodiesel. Rather, the results vary depending upon numerous factors – including engine type and configuration, duty cycle, fuel injection strategy, and emissions control strategy. Several theories have been developed to help understand these factors and explain the predominance of test data that show increased NOx with use of biodiesel. The major theories are briefly summarized below:

1. Speed of sound and bulk modulus of compressibility.

    In older style "pump-line-nozzle" (PLN) fuel injection systems, the fluid properties of speed of sound and isentropic bulk modulus of compressibility affect the injection process. Compared to petroleum fuel, biodiesel is less compressible and has a higher speed of sound, both of which contribute to an advance in fuel injection timing. Injection timing advance can lead to earlier start of combustion, which raises peak in-cylinder temperature, thereby increasing thermal NOx formation. With more advanced "common rail" electronic-controlled injection systems that are typically used today, the speed of sound and bulk modulus no longer affect the injection process; thus, the inadvertent timing advance when using biodiesel no longer occurs.

2. Prompt NOx formation.

    Prompt NOx (or Fenimore NOx) arises via reaction processes involving hydrocarbon fragments. It is thought that due to high levels of unsaturated compounds, combustion of FAME may produce more hydrocarbon radicals than combustion of conventional diesel, thus leading to higher NOx formation.

3. Decreased Radiative heat loss.

    It is well known that use of biodiesel reduces PM (or soot) emissions substantially. Within the combustion chamber, soot particles' are effective in radiative heat transfer, thereby lowering the overall flame temperature. A reduction in soot concentration would lead to higher combustion chamber temperatures, thereby increasing thermal NOx formation. This theory is consistent with the observation that use of biodiesel generally reduces PM while increasing NOx.

4. Adiabatic flame temperature.

    Combustion of model compounds has shown that unsaturated molecules exhibit higher adiabatic flame temperature than their saturated counterparts. This has been used to hypothesize that biodiesel gives higher flame temperature than conventional diesel, due to the high concentration of unsaturated compounds in biodiesel. Because of this higher temperature, increased thermal NOx formation would be expected.

5. Other fuel explanations.

    It has been suggested that the narrower boiling point, lower volatility, and higher density of FAME could affect the injection and combustion processes in ways that increase NOx emissions. Theories involving cetane number have also been proposed. Within a range of biodiesel types, NOx emissions have been observed to decrease as cetane number increases. In fact, use of cetane improvers has been explored as a means of mitigating the biodiesel NOx effect.

6. Other injection/combustion theories.

    During the pre-mixed combustion period, fuel and air that have already mixed ignite, causing a rapid rise in temperature and pressure. The extent to which these temperature and pressure increases occur depends upon the amount of fuel that has already been injected, which is related to the length of the ignition delay. With longer ignition delays (related to low cetane number), more fuel is injected and mixed with air before ignition occurs, thus leading to more extreme temperature and pressure increases. Several laboratory studies have shown a relationship between

the fraction of biodiesel fuel combusted during the pre-mixed period and the amount of NOx emissions. Because of biodiesel's oxygen content, it may pre-mix more thoroughly during the ignition delay period than conventional diesel fuel, such that a greater fraction of biodiesel burns during this period, resulting in larger heat release and increased thermal NOx formation.

7. Engine control/calibration theories.

   Modern diesel engines are equipped with electronic engine control modules (ECMs) that are programmed to control air/fuel ratios, injection timing, EGR, and other important parameters. The control strategy typically employs measurements of engine speed and torque, which are used to define operating conditions that maximize fuel economy while satisfying emissions requirements. Programming of the ECM control settings is generally based upon use of conventional diesel fuel. If use of biodiesel causes perceived changes in speed or torque, the ECM can make adjustments to operating conditions that result in higher emissions.

It is now generally understood that the biodiesel NOx effect results from a combination of engine control mechanisms and fuel/combustion mechanisms. Depending upon specific operating conditions, these different mechanisms can either reinforce or cancel one another. No single mechanism or fuel property can fully explain the biodiesel NOx effect. The controlling mechanism(s) often appear to be different between high and low engine load conditions.

Despite the small and variable effects of biodiesel on NOx emissions, a consensus has developed regarding certain fuel properties that are responsible for these effects. It is generally accepted that NOx emissions increase with increasing unsaturation, but decrease with increasing chain length.

The NOx effect that is usually observed with biodiesel is regarded as a problem requiring mitigation. Numerous mitigation approaches involving engine modifications and fuel modifications have been explored. Common engine modifications include retarded injection timing, phased injection, and use of EGR. Several investigators have applied all three of these modifications simultaneously in a combustion process known as low temperature combustion (LTC). With LTC, ignition delay increases, thus increasing the pre-mixed combustion phase and decreasing (or eliminating) the diffusion flame combustion phase. The overall in-cylinder temperature is reduced substantially, thereby reducing NOx formation. At the same time, PM is reduced due to the dominance of lean, pre-mixed combustion.

Fuel modifications for mitigating biodiesel's NOx effect include reduction of the base fuel's aromatic content, addition of cetane improvers, use of anti-oxidants, and addition of blendstocks that are inherently low NOx emitting – such as Fischer-Tropsch fuels or renewable diesel. The reported effectiveness of these approaches varies considerably throughout the literature. There is some indication that these measures will become less effective with newer engine technologies that already meet very low NOx emissions requirements.

With NOx emissions standards becoming increasingly stringent, exhaust after-treatment systems are now being introduced to meet the NOx requirements in both LD and HD applications. Two types of after-treatment approaches commonly employed are: (1) NOx adsorber catalyst (NAC), which is sometimes called a lean-NOx trap, and (2) selective catalytic reduction (SCR). Both NAC and SCR are generally used as components within more extensive after-treatment systems that also include PM traps, oxidation catalysts, O_2 sensors, and other devices. Optimized performance of a complete aftertreatment system requires sophisticated monitoring and control capabilities. Engine and vehicle manufacturers employ various proprietary strategies to integrate and control the multiple components within a complete after-treatment system. Because of variations in control strategies and performance of systems under different operating conditions, it is not likely that biodiesel would provide a consistent NOx effect in all situations.

Based upon the information currently available, it appears that use of biodiesel – especially at blend levels of B20 and below – does not seriously affect the performance of after-treatment systems. However, as these systems have been in commercial use for only a short time, further long-term study is warranted.

5.   Life-Cycle Assessments

Life-cycle assessments (LCA) are increasingly being used to support regulations and policies that promote sustainable use of renewable fuels. For example, California's Low Carbon Fuel Standard (LCFS), EPA's Renewable Fuel Standard (RFS2), the EU's Renewable Energy Directive (RED), and the UK's Renewable Transport Fuel Obligation (RTFO) all include application of LCA.

In the earlier CRC AVFL-17 project, published LCA studies were reviewed and compared. Both energy return (ER) and carbon intensity (CI) of biodiesel fuels were investigated on a life-cycle basis. Different modeling methodologies were reviewed, and the critical impacts of certain assumptions -- especially co-product allocation, N_2O emissions, and land use change (LUC) -- were highlighted. This current report provides updated information in all these topic areas, and includes summaries of more recent LCA studies. Particular focus is placed on CI results from studies used to support renewable fuel policies, with an emphasis on land use change effects -- both direct (DLUC) and indirect (ILUC).

To accurately estimate the life-cycle CI value for a biodiesel fuel scenario, extensive data are required on all inputs, products, and emissions from each life-cycle stage. Numerous modeling tools and databases have been constructed to support fuel LCA. Commonly used models include BEES, BESS, EBAMM, EcoIndicator, EIO-LCA, LEM, GaBi, GHGenius, GREET, GEMIS, and SimaPro. Commonly used databases include NREL's US LCI Database and EcoInvent. The GREET model, developed by Argonne National Laboratory, offers over 200 specific pathways for alternative fuels and vehicles. It is used by the EPA for their Renewable Fuel Standard (RFS2) assessments. CARB has modified the GREET model with data specific to California, and has used the resulting CA-GREET model in support of its LCFS.

Increasing biofuel production to meet policy targets will likely require additional lands to grow sufficient feedstocks, resulting in both direct and indirect land use change (DLUC and ILUC). DLUC is defined as LUC that can be attributed to the production of the biofuel itself, e.g., expansion of new cropland occurs to produce the feedstock directly. ILUC results if an existing crop is diverted to biofuel production, triggering a market response that leads to cropland expansion elsewhere. The effects of land use change (LUC) and how it is considered in LCA and policy has drawn considerable attention. In particular, the area of ILUC has been the focus of much debate. Many agree that ILUC has some impact, and should not be ignored. LCA models that include ILUC are complex, requiring inputs from economic models that generate feedback loops to reflect how changes in supply and demand affect price elasticity and co-product markets. These models produce high levels of uncertainty in the results, and include concerns about overlapping boundaries and double-counting of emissions. In addition, assumptions about the indirectly affected croplands are very influential, but highly uncertain. These include the following factors:

- Geographic location where the LUC occurs
- Amount of land affected
- Soil and vegetative characteristics of the affected land
- Time period that the land remains in production

Because of its extremely high global warming potential, the manner in which nitrous oxide (N_2O) is treated in LCA studies critically affects the overall CI of a biodiesel scenario. Most N_2O results from biological conversion of nitrogen in the soil (applied as fertilizer). Different researchers and organizations recommend different "N_2O conversion factors" to define the amount of N_2O emissions as a fraction of the

total nitrogen applied to the soil. The question of what is the correct N_2O conversion factor is important, but overly simplistic, since actual conversion of soil nitrogen to N_2O varies with soil conditions, crop type, and other factors.

Several co-products are produced throughout the manufacturing processes of biodiesel and renewable diesel. Common practice in LCA modeling is to allocate some of the environmental impacts to these co-products. At least four major allocation methods exist, with each one having its own set of pros and cons: (1) physical allocation, (2) economic allocation, (3) expanded allocation, and (4) no co-product allocation. The choice of allocation method can significantly affect the final CI result for a biodiesel fuel scenario. To enable reasonable comparison of different LCA studies requires that co-allocation methods be clearly defined, with model borders and assumptions being evident.

Through review of the literature, a database of over 40 LCA studies and associated CI results was constructed. The primary CI functional unit used in this database is g $CO_{2\ eq}$/MJ$_{fuel}$. In addition, the database summarizes the biodiesel feedstock type, location of feedstock production, fuel production method, co-product allocation method, N_2O conversion value, and other important factors. Many LCA studies explored a range of scenarios, providing a set of different CI results for different cases. In summarizing and portraying results across the entire dataset of studies, representative cases, or those identified as "best cases," were selected.

In assessing the overall data, CI results for each study were segregated and plotted for five feedstock types: soybean, rapeseed, palm, yellow grease, and other oils. Figure TS-7 shows an example for the soybean-derived fuels. Both biodiesel and renewable diesel fuels are included, along with the reference petroleum diesel fuel corresponding to each biodistillate case. In nearly all cases, the reference petroleum diesel fuel gave a CI value of 80-100 g CO_{2eq}/MJ$_{fuel}$. CI results for the soybean-derived biodistillates varied greatly, though most fall between 20 and 60 g $CO_{2\ eq}$/MJ$_{fuel,}$ thus showing significant reductions compared to the petroleum diesel fuel reference. Considering the large variability in these CI results, it is not possible to draw firm conclusions about the effects of different biodiesel types. Nevertheless, it appears that a CI benefit of approximately 50-60% results from biodistillates produced from virgin vegetable oil feedstocks, and a slightly larger benefit results from use of the waste feedstocks of tallow and yellow grease. (Waste feedstocks generally give lower CI values because no cultivation or transportation emissions are attributed to them.)

For most feedstocks, renewable diesel shows a slightly more favorable CI result than biodiesel. However, fewer studies have been completed for renewable diesel in general, and many of them are published by the renewable diesel industry. More sophisticated data analysis techniques (and a more robust database) would be required to clearly establish differences between biodiesel and renewable diesel cases.

Despite the importance of ILUC effects, very few LCA studies conducted to date have included consideration of these effects. Two that have are highlighted in Figure TS-7: Study No. 113 – by CARB, and Study No. 127 – by EPA. In both cases, inclusion of ILUC (indicated by the upper plotted data points) dramatically increased the overall CI values of these soy biodistillates – from 21 to 83 g CO_2 $_{eq}$/MJ$_{fuel}$ in the CARB case; from 8 to 40 g $CO_{2\ eq}$/MJ$_{fuel}$ in the EPA case.

Figure TS-7 Carbon Intensity of Biodistillates Produced from Soybean Oil
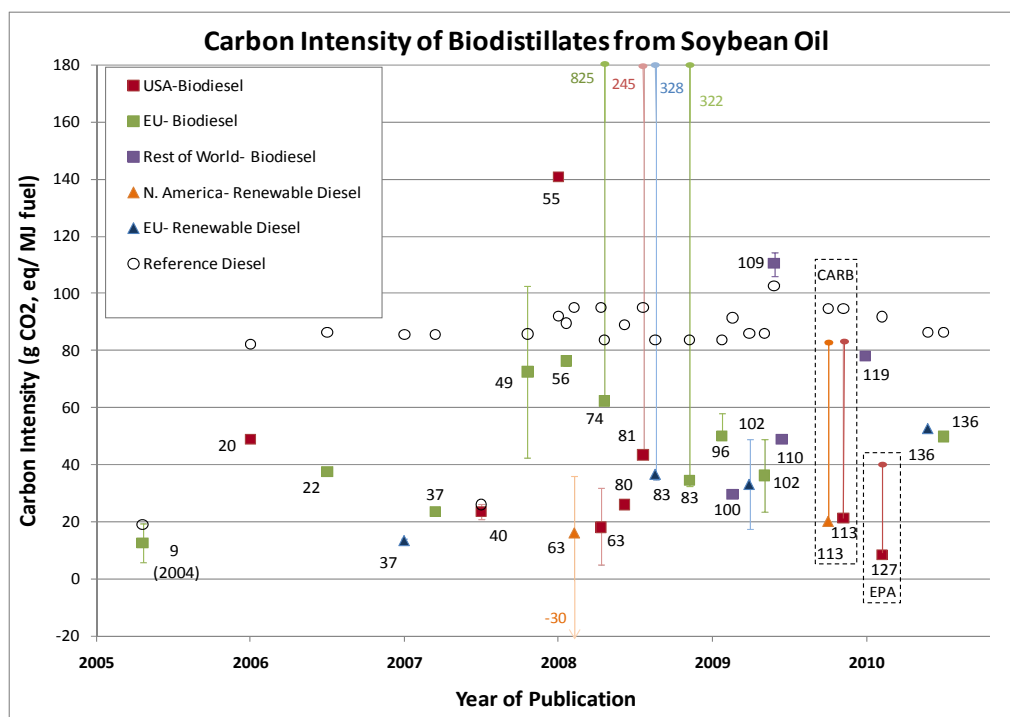
A simplified representative CI breakdown of the EPA's LCA categories for biodiesel is shown in Figure TS-8. The categories that gave decreased emissions are represented in the "offsets" bar. The overall result from this soy-based biodiesel scenario (including ILUC of 31.9 g $CO_{2\,eq}$/MJ$_{fuel}$) shows a CI value of 39.8 g $CO_{2\,eq}$/MJ$_{fuel}$, compared to a reference diesel fuel baseline of 91.8 g $CO_{2\,eq}$/MJ$_{fuel}$. Therefore, soy-based biodiesel is determined by EPA to provide a 57% reduction in GHG on a life-cycle basis, which meets the required threshold value of 50% for biomass-based diesel fuel defined in the RFS2 regulations.

The effects of ILUC are modeled independently in the CARB study (Study No. 93) and then added to the standard life cycle effects for biodiesel from soybeans grown in the Midwest, as shown in Figure TS-8. CARB's computed ILUC CI ranged from 43 to 93 g $CO_{2,eq}$/MJ$_{fuel}$,. An average value for all cases was determined (for total land conversion area of 0.94 million hectare), and was adjusted to 62 g $CO_{2,eq}$/MJ$_{fuel}$ to account for yield increases between 2001 and 2004. Applying this ILUC CI to the biodiesel baseline LCA value of 21.25 g $CO_{2,eq}$/MJ$_{fuel}$ gives a total CI of 83.25 g $CO_{2,eq}$/MJ$_{fuel,}$ which represents a 12.1% reduction from the petroleum diesel base.

A few individual researchers have also investigated the impacts of ILUC on lifecycle GHG emissions of biodiesel. One of the best known studies was published by Searchinger and Heimlich in 2008. The CI breakdown for soybean-derived biodiesel as computed in this study, shows a sizable positive value for combustion GHG emissions (orange bar segment in Figure TS-8), along with an equally large offset for plant uptake of GHG. The life-cycle emissions from cultivation and production are much larger than in the CARB or EPA study. Searchinger concluded that a significant increase in CI occurred because of ILUC required to increase production of soy biodiesel. Because of this large ILUC effect, the final CI result for the soybean-based biodiesel scenario was much higher than the petroleum diesel base case.
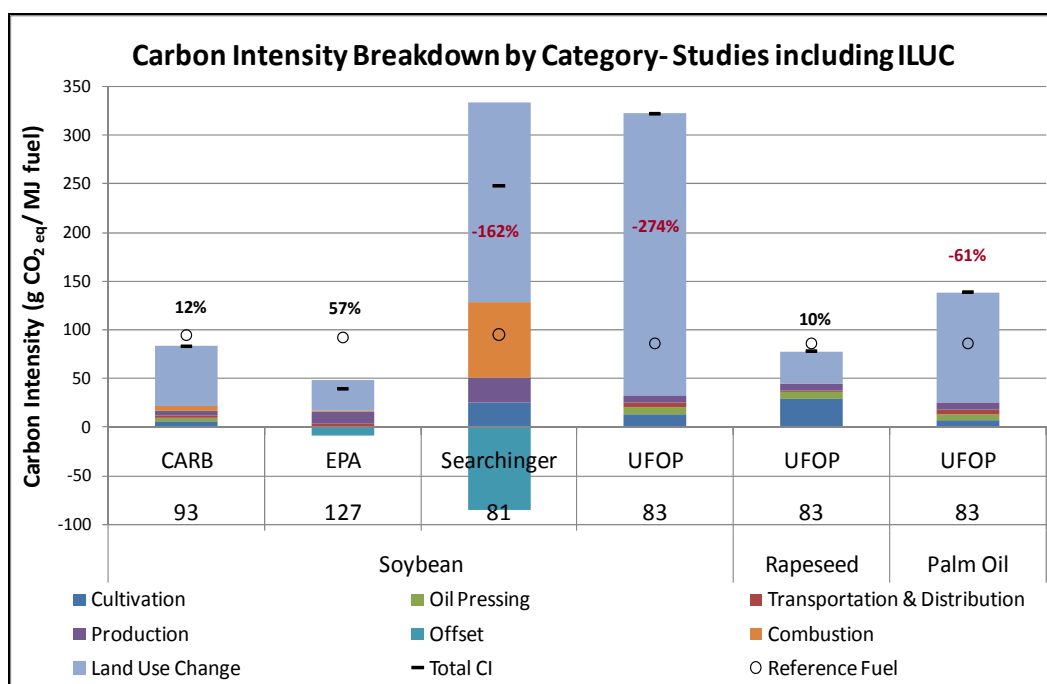
Figure TS-8. Carbon Intensity Breakdown by Life-Cycle Stage – Impact of ILUC on Biodiesel

A German organization called UFOP considered the impacts of DLUC occurring in foreign lands used to provide increased biodiesel for the European market. (In effect, this situation is the same as ILUC.) For soybean-derived biodiesel, feedstocks from both North America and Latin America were investigated. The very large ILUC value of 290 g CO_{2eq}/MJ_{fuel} shown in Figure TS-8 comes from the Latin American scenario, where native savannah lands are assumed to be used for growing soybeans. Similarly, a high ILUC CI impact of 113 g $CO_{2\,eq}$/MJ_{fuel} was estimated for palm oil, which was assumed to involve expansion of agriculture into Southeast Asian rainforests. Rapeseed biodiesel is the only one to show a GHG benefit, however small. In this case, the rapeseed is assumed to be grown locally, on EU croplands. Even in this case, the ILUC effects are significant, decreasing the CI benefit from 48% to less than 10%.

While very few studies model ILUC, there are significant discrepancies among those that do. To fully understand these differences and make robust analyses of ILUC, a transparent data set and model boundaries must be described. Additionally, while many agree that agriculturally-related ILUC is important, other drivers for land use change also exist, such as socio-economic changes, technological changes, and population changes.

6. Regional Fuel Specifications and Quality

One of the principal means of ensuring satisfactory in-use biodiesel fuel quality is establishment of a rigorous set of fuel specifications. The two most common biodiesel standards are ASTM D6751 (in the U.S.) and EN 14214 (in the European Union). Many other countries have defined their own standards, which in most cases are derived from either ASTM D6751 or EN 14214.

Another means of ensuring satisfactory biodiesel product quality involves establishment and enforcement of quality control/quality assurance (QC/QA) programs. The two best known programs are the German Association for Quality Management of Biodiesel (AGQM) and the BQ-9000 Quality Management System developed by the U.S. National Biodiesel Board (NBB). The BQ-9000 system has recently been expanded to include a set of requirements for biodiesel laboratories, in addition to the existing

requirements for biodiesel producers and marketers. The BQ-9000 Program includes a combination of ASTM standards and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices.

Several organizations have defined in-use handling guidelines to help ensure satisfactory biodiesel quality in the marketplace. Two of the most extensive guidelines have been produced by NREL and CONCAWE. These documents address common field problems involving oxidative instability, cold temperature handling, microbial contamination, and other practical issues.

In-use field surveys have also been conducted to assess the quality of biodiesel blendstock (B100) and measure the FAME levels in biodiesel blends. Early surveys revealed problems with both blending accuracy and with the quality of B100. More recent surveys indicate that fuel quality has improved.

7.   Summary and Conclusions

Biodiesel Composition

- There is growing consensus regarding the fatty acid (FA) profiles of vegetable oils and animal fats commonly used to produce fatty acid methyl esters (FAME). Clear differences in carbon chain length and degree of unsaturation are apparent from one feedstock to the next. These differences influence the properties and performance of biodiesel (FAME) and biodiesel blends.

- The compositional profiles of common vegetable oils are dominated by five fatty acid species: palmitic (16:0), stearic (18:0), oleic (18:1), linoleic (18:2), and linolenic (18:3). Coconut oil is significantly different, containing large fractions of lighter fatty acid species – especially lauric (12:0) and myristic (14:0). Camelina is also somewhat different from most other vegetable oils, with linolenic acid (18:3) being its largest single constituent, along with smaller amounts of higher molecular weight species, 20:1 and 22:1.

- Jatropha also appears somewhat unusual in that it contains a significant level (2-3%) of a high molecular weight FA, lignoceric acid (24:0). However, this result is quite uncertain – with only a few literature reports mentioning this substance – and requires further confirmation.

- Compared to vegetable oils, relatively little detailed FA compositional information is available for algal lipids. However, it is clear that compositional variability across different algal species can be extreme. Some species have much higher levels of unsaturation – and especially multi-unsaturation – than is typical for vegetable oils. The high variability in algal lipid FA compositions is partly due to the fact that compositions vary with growth conditions.

Biodiesel Properties

- The physical and chemical properties of a biodiesel are largely determined by its chemical composition. Due to its considerable oxygen content (typically about 11%), biodiesel has lower carbon and hydrogen contents compared to petroleum diesel. This results in a reduction in mass energy content of about 10%.

- Two properties that greatly influence the overall behavior and suitability of FAME as a diesel blendstock are: (1) the size distribution of the fatty acid (FA) chains and (2) the degree of unsaturation within these FA chains. Variations in biodiesel produced from different feedstocks can be explained in large part by these two properties.

- The two most common sets of regulatory standards for biodiesel blendstocks are ASTM D6751 in the U.S. and EN 14214 in Europe. Some specifications comprising these standards are directly related to the chemical composition of FAME – such as viscosity, cetane number, cloud point, distillation, and iodine value. Other specifications relate to the purity of the FAME product, and address issues pertaining to production processes, transport, and storage – such as flash point, methanol content, metals content, sulfur level, acid number, and cold soak filterability.

- Oxidative stability is an important property of biodiesel that is determined by both FAME chemical composition and by storage and handling conditions. Fuel oxidation is related to unsaturation within the FA chain, and is especially promoted by multiple units of unsaturation. For this reason, the oxidative stability of camelina-based FAME and some algal-based FAME may be of concern.

- Several important physical and chemical properties were compiled and compared for biodiesel fuels produced from 12 different vegetable oil and animal fat feedstocks. Some properties are highly correlated, such as various low temperature performance properties. Iodine value and cetane number are highly correlated, while cetane number and cetane index are not correlated.

- A computed fuel property, called "average unsaturation," was highly correlated with several other properties, including viscosity, specific gravity, low temperature performance metrics, cetane number, and iodine value. An increase in average unsaturation leads to lower cetane number and poorer oxidative stability, but improved low temperature performance. Another computed property, "average chain length," was not well correlated with most other properties. To more clearly distinguish the independent effects of unsaturation and chain length (and other properties) in complex fuel mixtures requires use of sophisticated statistical analysis techniques.

- Of the 12 biodiesel types that were investigated, coconut-derived FAME is unusual with respect to viscosity, density, flash point, iodine value, and heating value. This stems from coconut oil's compositional profile, which is dominated by short FA chains (especially C_{12}) and very low unsaturation (< 10% total unsaturates). Because of these properties, the suitability of coconut-derived FAME as a diesel blendstock is somewhat questionable.

- An increasingly recognized problem with some biodiesel fuels is their propensity to form insoluble precipitates upon storage at low temperature. In large part, this problem is believed to be due to the presence of trace impurities – particularly sterol glucosides and saturated monoglycerides. These same impurities impart favorable lubricity performance to biodiesel; thus efforts to eliminate them could have an unintentional consequence of worsening lubricity.

- Due to the conflicting impacts of certain FAME compositional features upon different fuel properties, it is not possible to define a single composition that is optimum with respect to all important properties. However, for good low temperature performance, biodiesel should have low levels of saturated FA; for good oxidative stability, biodiesel should have low levels of multi-unsaturated FA.

Emissions

- Using a larger and more robust database than in the previous AVFL-17 study, the effects of biodiesel usage upon emissions were examined in both HD and LD engines/vehicles. These results generally confirmed earlier findings (with HD engines) that with increasing B-level, HC, CO, and PM emissions decrease substantially, but NOx increases slightly. Results from HD

chassis testing are similar, though not identical. Results from LD testing are more variable and quite different, showing small increases in CO, PM and NOx with increasing B-level.

- The largest number of emission test results originates from use of B20 blends. Different data sorting methods were used to inspect these B20 results and investigate the effects of biodiesel feedstock, base fuel type, engine model year, and test cycle. The high degree of variability prevents firm conclusions from being made. More sophisticated data analysis techniques (and perhaps a larger dataset) would be required to discern these subtle effects.

- The reported impacts of biodiesel upon aldehyde emissions are very inconsistent. Numerous examples of both aldehyde increases and decreases with changes in B-level are given in the literature. Generally, formaldehyde and acetaldehyde are the dominant emission species, although there are several reports where others – such as acrolein, proprionaldehyde, crotonaldehyde, benzaldehyde, and others – are significant contributors to the total aldehyde emissions.

- Acrolein is an aldehyde of particular interest, since it is classified by EPA as a mobile source air toxic (MSAT), along with formaldehyde and acetaldehyde. The available data regarding impacts of biodiesel upon acrolein emissions is very sparse and uncertain. Acrolein is somewhat difficult to quantify because of its reactive nature. Also, some analytical methods commonly used to measure a variety of individual carbonyl compounds derivatives cannot reliably quantify acrolein.

- The beneficial impact of biodiesel in reducing PM emissions is largely a consequence of fewer accumulation mode particles. Under some conditions, the number of smaller, nucleation mode particles has been found to increase with use of biodiesel. These so-called nanoparticles likely arise from condensation of unburned fuel or fuel impurities, and are expected to be readily removed by a diesel particulate emissions after-treatment system.

- The amount of information available regarding PAH emissions is very limited. Although no firm conclusions can be made, it appears that use of biodiesel reduces or has no effect on PAH emissions. As the magnitude of these effects is rather small, they are unlikely to be significant when using low concentration biodiesel blends, such as B20.

- The effects of biodiesel usage upon NOx emissions are not consistent across all engine types, operating modes, and fuel compositions. Improved understanding of the so-called "NOx effect" has been gained in recent years. The increased speed of sound in biodiesel (compared to petroleum diesel) and bulk modulus of compressibility were once used to explain increased NOx emissions resulting from an inadvertent advance in fuel injection timing. This situation still exists in part of the legacy fleet, but is largely a problem of the past, having been eliminated by advancement in fuel injection technology.

- In modern diesel engines, multiple inter-related factors contribute to the overall NOx effect. These include fuel compositional factors, fuel injection strategies, engine load conditions, and engine control/calibration approaches. There is considerable evidence that with all other factors being equal, NOx emissions increase with increasing fuel unsaturation and decreasing chain length.

- Numerous approaches have been investigated to mitigate the NOx effect when using biodiesel blends. Fuel modifications that have demonstrated various degrees of success include reduction of aromatic content, addition of cetane improvers, addition of anti-oxidants, and blending with highly paraffinic stocks, such as F-T fuels. Engine modifications for NOx control include

retarded injection timing, split injection techniques, and use of EGR. An extreme example of these engine modifications results in operation known as low temperature combustion, which offers the possibility of simultaneous NOx and PM reductions.

- With today's sophisticated electronically-controlled engines, it seems likely that the historic, adverse NOx effect from use of biodiesel can be eliminated. However, for this to succeed, a reliable fuel sensor must be utilized, so that the engine operation can be optimized for the particular fuel being used.

- To meet increasingly stringent exhaust emissions standards, NOx after-treatment systems are now being introduced. Two general types are employed: one involving selective catalytic reduction (SCR) using ammonia as a reducing agent; the other involving NOx adsorber catalysts (NAC). Because these systems are still quite new, there is little information available about their in-use durability, or the impacts that biodiesel usage may have on them.

Life-Cycle Analyses and Carbon Footprint

- The literature for life cycle assessments (LCA) of biofuels is growing rapidly in response to requirements that LCA approaches be used to support alternative fuel policies and GHG reduction strategies.

- The topic of indirect land use change (ILUC) has become the focus of much attention. Although there are numerous publications discussing the merits of ILUC, only a handful of studies have attempted to model the ILUC of biodiesel fuels. These show that the impacts can be quite substantial, with carbon payback periods reaching hundreds of years in some worst-case scenarios.

- Many regulators and policy-makers now agree that ILUC should be included in LCA studies of biofuels. Consequently, both U.S. EPA and CARB include ILUC in their renewable fuel policies, while EU is still evaluating the best practices and methodologies by which to include ILUC.

- The best practices for modeling ILUC are still under discussion. Assumptions of where the land use is occurring, how much land is affected, the soil and vegetation characteristics, and the time frame over which the land use changes occur significantly influence the results. Approaches followed by CARB and EPA have undergone extensive peer review. These approaches integrate several modeling tools in an attempt to accurately represent life-cycles and their emissions impacts. Both agencies have opted to use a 30-year time horizon and a zero % discount rate.

- Other influences of feedstock type (rapeseed, soy, etc.) and fuel type (biodiesel and renewable diesel) have been investigated. Excluding ILUC, there appear to be slight differences between feedstock type, with waste feedstocks (tallow and yellow grease) giving more favorable carbon intensity (CI) values than non-waste feedstocks, such as soy, rapeseed, and palm.

- LCA studies of the two most common biodiesel feedstocks, soy and rapeseed, do not show consistent CI differences. LCA studies of "next generation" feedstocks such as jatropha and algae are increasing, but there are still too few of these to draw any firm conclusions. Similarly, no significant differences are seen in CI results from biodiesel compared to renewable diesel, though directionally, renewable diesel appears to be slightly more favorable. To reliably quantify such subtle effects would require additional, carefully matched modeling studies, and more sophisticated data analysis techniques.

- A consensus has not yet been reached on other significant LCA assumptions, such as co-product allocation or N_2O conversion ratios. N_2O emissions may be compounded for ILUC effects, increasing both when new land is converted, and when an intensification of growth on existing land occurs. Since the global warming potential (GWP) of N_2O is very high, small changes in emissions can have large effects on CI.

- Because the modeling approach and input assumptions of each LCA study can vary significantly, direct comparison of final CI values should be done with extreme caution.

Regional Fuel Specifications and Quality

- Many countries have now adopted standard specifications for biodiesel fuel (B100). Most of these standards are patterned after those established in the U.S. (ASTM D6751) and Europe (EN 14214). These standards are constantly evolving to address new concerns about fuel quality and performance, and to accommodate introduction of improved analytical test methods.

- Surveys of in-use biodiesel fuel quality have been conducted in the past, and have revealed some concerns about blending accuracy and adherence to fuel specifications. More recent surveys have shown improved quality. It may be advisable to conduct similar in-use fuel quality surveys again, since significant changes in fuel specifications (addition of Rancimat oxidative stability test and low temperature filtration test) and QA/QC practices (expansion of the BQ-9000 Process) have occurred recently.

1. INTRODUCTION AND BACKGROUND

Interest in biodiesel is continuing to increase in the U.S. and throughout the world. This is motivated primarily by: (1) concerns about greenhouse gas (GHG) emissions and global climate change, (2) a desire for renewable/sustainable energy sources, and (3) an interest in developing domestic and more secure fuel supplies. In recent years, several countries (and states) have embarked on legislative and/or regulatory pathways that encourage increased use of biodiesel fuel – using both incentives and prescriptive volumetric requirements. For example, in the U.S., the Energy Independence and Security Act (EISA) of 2007 established a 0.5 billion gallon/year (bg/y) requirement for biomass-based diesel fuel in 2009, with this amount increasing to 1.0 bg/y by 2012. [1] Figure 1 illustrates how this biomass-based diesel volumetric requirement contributes to the overall renewable fuel requirement of 36 bg/y by the year 2022.
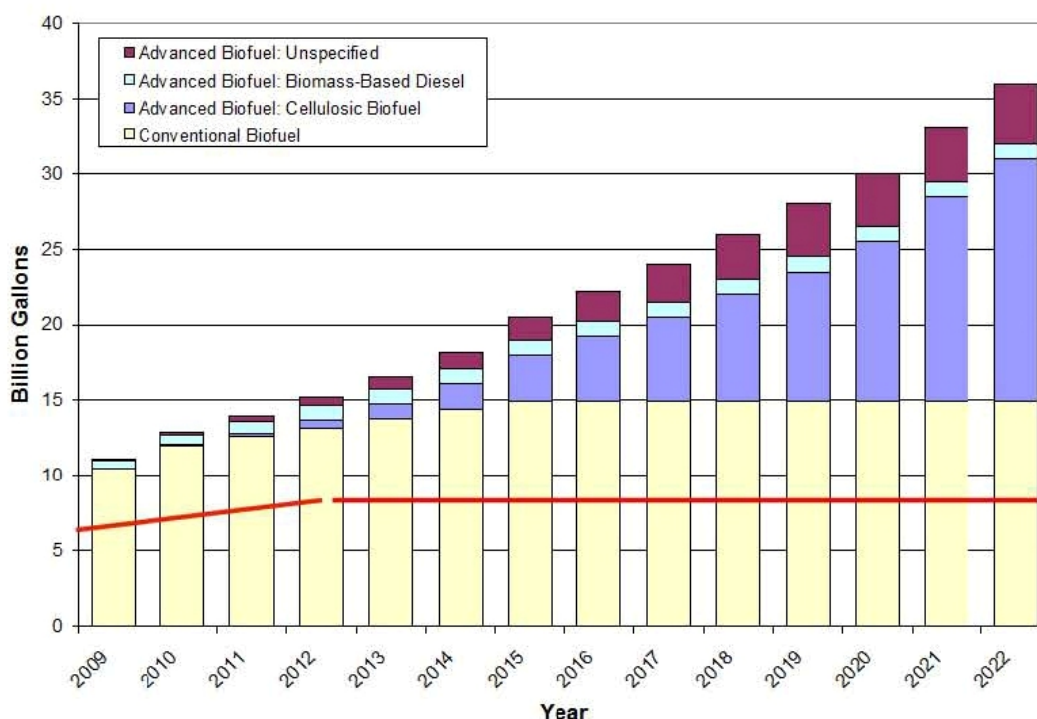
Figure 1. U.S. Renewable Fuel Requirements
(Graph obtained from Stoel Rives [2].
Red line indicates previous requirements under the 1995 Energy Policy Act.[3])

1.1 Previous Study

With the biodiesel landscape being in a state of rapid flux, CRC recently sponsored Project AVFL-17 to define the state-of-knowledge regarding biodistillates as blendstocks for transportation fuels. Utilizing an extensive literature review, the following biodistillate topics were investigated:
- policy drivers
- fuel volumes and feedstocks
- production technologies
- fuel properties and specifications
- in-use handling and performance
- emissions impacts
- life-cycle analyses

The final report from this previous CRC study contained fairly broad coverage of a wide range of topics related to biodistillates.[4] Many of these topics were also covered in a series of three SAE Papers that were derived from the AVFL-17 final report.[5,6,7] (The generic term "biodistillate" was used to indicate that both biodiesel and renewable diesel fuel were included in the review.) The final report also pointed out that a large amount of new information relevant to biodistillates was appearing in the literature at a rate of about 20-30 items per month.

1.2   Updated Study

With such a rapid increase in information, CRC wished to undertake an updated review of the biodistillate literature. In addition, increased biodistillate usage in the marketplace, and changes in legislative and regulatory arenas related to biofuels, makes such an update especially timely. Since biodiesel is the dominant biodistillate in the marketplace, this updated review focuses on biodiesel, as opposed to renewable diesel fuel.

Rather than a broad review of many topic areas, as was done previously, this updated study focuses on three specific areas of biodiesel issues.

1. Relationships between the composition of biodiesel and fuel properties, performance, and emissions. The impacts of different biodiesel feedstocks are of interest, such as soy, rapeseed, jatropha, etc. Also important are the impacts of the base diesel fuel into which biodiesel is blended to produce B20 and other blends, and impacts of the engine technology being used.

2. Greenhouse gas (GHG) emissions and the life-cycle GHG impacts of specific biodiesel scenarios as compared to petroleum diesel. This area has become very important, as some legislative and regulatory measures now require life-cycle assessments (LCA) of biofuels. For example, EPA's advanced renewable fuel standards (called RFS2) requires that each type of renewable fuel – including "biomass-based diesel" – satisfy a defined GHG reduction baseline, on a life-cycle basis. [8,9] In addition, California's Low Carbon Fuels Standards (LCFS) require that carbon intensity (CI) of transportation fuels be reduced at least 10% by 2020.[10]

3. Fuel specifications that pertain to biodiesel fuel in various countries, and issues related to in-use fuel quality.

1.3   Definitions and Limitations

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." [11] Congress has adopted a similar definition for "Biomass-based diesel," with the additional requirement that the fuel have life-cycle greenhouse gas (GHG) emissions that are at least 50% less than baseline life-cycle GHG. [1] The vegetable- and animal-derived feedstocks used to produce biodiesel are known as triacylglycerides (TAGs), or more simply, triglycerides. Biodiesel is produced by a chemical process known as transesterification, by which the triglycerides are reacted with alcohols, in the presence of a catalyst, to produce fatty acid alkyl esters. A byproduct of transesterification is glycerine, also known as glycerol. Since the most common alcohol used to produce biodiesel is methanol, another name for biodiesel is fatty acid methyl esters (FAME). Unless otherwise indicated, the term "biodiesel" refers to neat material – i.e. 100% FAME, often designated as B100. Lower concentrations, such as B20, are properly referred to as "biodiesel blends," not biodiesel itself. A listing of other common acronyms and abbreviations is provided in Appendix I.

Renewable diesel fuel (also known as Green Diesel) is produced by catalytic hydroprocessing of the same triglyceride feedstocks used to produce biodiesel. In this process, an alcohol is not required, the products are hydrocarbons rather than fatty acid alkyl esters, and no glycerol byproduct is formed. The general

term "biodistillate" is used to refer to both biodiesel and renewable diesel. A more complete glossary of fuel terms is provided in Appendix II.

Terminology regarding "1st Generation" and "2nd Generation" biofuels requires further 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 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). 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 to produce renewable diesel, and thermal conversion (gasification and pyrolysis) of lignocellulose. Because of their imprecise and variable meanings, this report avoids use of the terms 1st Generation and 2nd Generation (and related terms).

For the purposes of this study, investigation into biodiesel is limited to on-road transportation fuel applications, thus excluding other possible uses such as heating fuels and aviation fuels. Because of its common usage, the greatest emphasis is placed on FAME, although other forms of biodiesel are considered when appropriate. Also, when addressing GHG life-cycle issues, both biodiesel and renewable diesel scenarios are included. While use of neat biodiesel is of some interest, blends of biodiesel with petroleum diesel are much more commonly used. This study focuses on biodiesel blends with low sulfur diesel (LSD), and especially ultra-low sulfur diesel (ULSD) fuels.

1.4   Information Sources

Much of the effort in this study consisted of a thorough review of technical literature regarding the composition, properties, specifications, emissions impacts, and life-cycle GHG impacts of biodiesel. The previous CRC AVFL-17 report provided an excellent starting point, as over 1000 literature items of interest had already been screened. As in the previous, broader review [4], the literature search focused on recent years (2000 to the present) although selected older items of interest were also included. The principal sources used to locate relevant additional literature are the following five:

1. Web of Knowledge: 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.

The general approach was to begin with broad search terms such as "biodiesel" and "emissions," 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. A Thomson ResearchSoft computer program called

Reference Manager was used to help organize and store relevant literature. 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.

Because the subject areas related to biodiesel fuels are currently very active, with many new items of interest appearing in the literature each month, the authors updated their search several times throughout the course of this study. The final complete literature search update was conducted in April, 2010, although several more recent publications have also been included.

2. BIODIESEL COMPOSITION

Biodiesel fuel can be produced by transesterification of virtually any triglyceride feedstock. This includes oil-bearing crops, animal fats, and algal lipids. The literature contains hundreds of references of biodiesel production from a wide variety of feedstocks. At present, however, the dominant feedstocks are soybean oil in the U.S., rapeseed oil in Europe, and palm oil in Southeast Asia. [4,12] Animal fats (especially beef tallow) and used cooking oil (also called yellow grease) now represent significant niche markets for biodiesel in many locations. Other vegetable oils having real or potential commercial interest as biodiesel feedstocks include camelina, canola, coconut, corn, jatropha, safflower, and sunflower.

In addition, there is enthusiastic interest in developing and utilizing algal lipids as biodiesel feedstocks. 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. [13] Table I summarizes potential yields of biodiesel that could be produced from various triglyceride feedstocks. While many of these values are rather speculative, it appears that algae has the potential to produce significantly larger annual volumes of biodiesel per acre as compared to other sources.

Table I. Potential Biodiesel Output

Source	Potential Annual Yield, gallons/acre	Source of Info (Reference Nos.)
Corn	18-20	[14,15,16]
Cotton	35-45	[15,16,17]
Soybean	40-55	[12,14,15,18,16,19,17]
Mustard	60-140	[12,20]
Camelina	60-65	[20,21]
Safflower	80-85	[14,21,20]
Sunflower	75-105	[15,19,17,20]
Canola	110-145	[12,14,15,17,20]
Rapeseed	110-130	[22,19,21,17,20]
Jatropha	140-200	[12,15,23,19,21,20]
Coconut	250-300	[21,17,20]
Palm Oil	400-650	[12,14,15,19,21,17,20]
Algae	>5000*	[12,14,24,21,20,24]
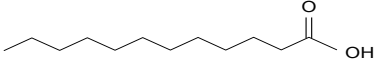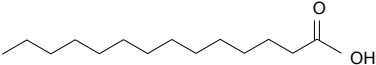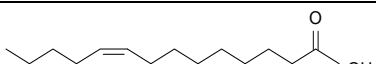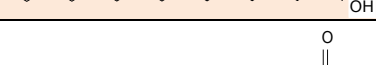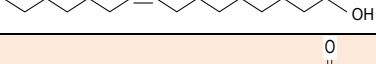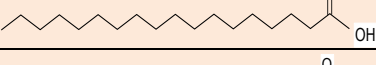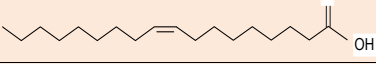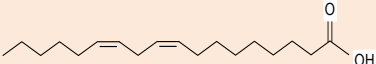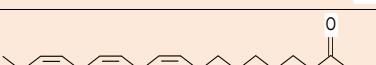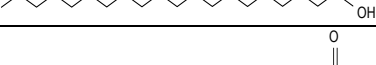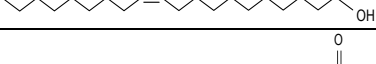
* Figure for algae is based upon extrapolations from small scale operations, and is quite speculative

Although biodiesel fuel produced from transesterification of triglycerides contains numerous individual FAME species, a particular fuel is generally dominated by only a few species. A list of fatty acids (FA) most commonly seen in biodiesel is provided in Table II. A simple FA naming convention is shown in

this table. This convention consists of two numbers, separated by a colon symbol. The first number refers to the number of carbon atoms in the FA chain; the second number refers to the number of carbon-carbon double bonds in the FA chain.

Of the 13 species shown in Table II, 5 typically dominate the composition of FAME derived from vegetable oils and animal fats: palmitic acid (16:0), stearic acid (18:0), oleic acid (18:1), linoleic acid (18:2), and linolenic acid (18:3). Some algal-derived lipids are also dominated by these same fatty acid groups, while other algae are more diverse in their composition, containing significant amounts of several other FA groups. Biodiesel (FAME) produced from transesterification of triglycerides, regardless of their source, is composed nearly exclusively of even-numbered FA chains. In contrast, renewable diesel produced from the same feedstocks contains substantial amounts of odd-numbered FA chains, since one carbon is removed during the hydroprocessing step used to manufacture renewable diesel.

Table II. Typical Fatty Acid (FA) Groups in Biodiesel

(shaded compounds are most common)

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	
Myristic Acid	Tetradecanoic Acid	544-63-8	14:0	$C_{14}H_{28}O_2$	228.38	
Myristoleic Acid	cis-9-Tetradecenoic Acid	544-64-9	14:1	$C_{14}H_{26}O_2$	226.26	
Palmitic Acid	Hexadecanoic Acid	57-10-3	16:0	$C_{16}H_{32}O_2$	256.43	
Palmitoleic Acid	cis-9-Hexadecanoic Acid	373-49-9	16:1	$C_{16}H_{30}O_2$	254.42	
Stearic Acid	Octadecanoic Acid	57-11-4	18:0	$C_{18}H_{36}O_2$	284.48	
Oleic Acid	cis-9-Octadecenoic Acid	112-80-1	18:1	$C_{18}H_{34}O_2$	282.47	
Linoleic Acid	cis-9,12-Octadecadienoic Acid	60-33-3	18:2	$C_{18}H_{32}O_2$	280.46	
Linolenic Acid	cis-9,12,15-Octadecatrienoic Acid	463-40-1	18:3	$C_{18}H_{30}O_2$	278.44	
Arachidic Acid	Eicosanoic Acid	506-30-9	20:0	$C_{20}H_{40}O_2$	312.54	
Gondoic Acid	cis-11-Eicosenoic Acid	5561-99-9	20:1	$C_{20}H_{38}O_2$	310.53	
Behenic Acid	Docosanoic Acid	112-85-6	22:0	$C_{22}H_{44}O_2$	340.60	
Erucic Acid	cis-13-Docosenoic Acid	112-86-7	22:1	$C_{22}H_{42}O_2$	338.58	

2.1 Compositional Profiles of Biodiesel from Fats and Oils

For the purposes of this report, 12 common fat and oil materials were considered as biodiesel feedstocks. These 12 materials are shown in Table III, which provides fatty acid (FA) compositional information for each one. Four of these 12 materials are predicted by EPA to provide the total volume of biodiesel needed to satisfy the RFS2 requirements by the year 2022: soy oil (660 mg/y), corn oil (680 mg/y), yellow grease (230 mg/y) and algae (100 mg/y). [9]

The compositional data shown in Table III were obtained by reviewing and summarizing numerous literature sources. Many literature references cite compositional data derived from other sources. Whenever possible, the authors obtained and reviewed the original sources. The data in Table III include both FA compositions of the triglyceride feedstocks, and FA compositions of biodiesel fuel (FAME) produced from these feedstocks. (It is generally assumed that FA compositional profiles remain unchanged during conversion of the feedstocks to fuels via transesterification.)

Table III also indicates the number of literature references used to obtain the average compositional profiles. These varied from 6 sources (for camelina) to 39 sources (for soy). Data obtained from the individual sources are given in Appendix IV, which shows that different researchers often reported quite different compositional profiles for the same materials. While actual compositions do vary somewhat based upon growing conditions and locations, most of this variability probably results from use of different analytical methods – and different skill levels in applying these methods.

We have found very few reports in the literature of carefully controlled studies that investigate the impacts of growth conditions (water, nutrients, temperature, etc.) upon the fatty acid profiles of vegetable oils. One recent controlled field experiment with Jatropha in Egypt demonstrated that the profile did not change dramatically with growth conditions, although the total amount of fatty acids did. [25] Another study, involving growth of sunflower in Argentina, inferred more significant changes in FA profile, based upon variations in iodine values, which correlate with degree of unsaturation. [26]

In this report, no *a priori* judgments were made regarding the validity of reported compositional data. All values were initially accepted, and weighted equally to compute a mean compositional result (wt. %) for each species. The distribution of values reported for an individual species (from a given feedstock) was then inspected, and values far from the mean (typically > 2 standard deviations) were identified. These "outliers" were first investigated by re-inspecting the original literature source and determining whether data entry errors were made. In some cases, even though no obvious errors could be identified, outliers were eliminated when calculating means and standard deviations. These instances are highlighted by shading the affected cell values in the tables of Appendix IV.

In very few cases, the authors adjusted the reported values for oleic acid (18:1) and linoleic acid (18:2), believing that these two were inadvertently switched by the authors. (When using GC-FID detection only, rather than GC-MS detection, it is relatively easy to misinterpret the chromatograms in this way.) One example of this is shown in the corn oil profile of Appendix IV. The overall average ratio of 18:1 to 18:2 is approximately 1:2, and most individual references report a ratio quite close to 1:2. Yet, one reference reports the opposite ratio of 2:1. As indicated by shading in the Appendix IV table for corn oil, the authors have reversed the 18:1 and 18:2 values that were originally reported.

The average profiles summarized in Table III have been adjusted by eliminating outliers – generally, these are values more than 2 standard deviations from the mean. Empty cells represent FA species that were not reported in any references the authors reviewed. Cases which show a mean value but no standard deviation indicate that only one reference was found for this FA. The reader will note that the sum of species in these average profiles does not equal 100%. In part, this is due to rounding issues. However, it

Table III. Fatty Acid Compositional Profiles of Biodiesel (FAME) from Fats and Oils

| Fatty Acid | | Camelina | | Canola | | Coconut | | Corn | | Jatropha | | Palm | | Rapeseed | | Safflower | | Soy | | Sunflower | | Tallow | | Yellow Grease | |
Common Name	Abbrev.	mean	dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev
Capriotic	6:0					0.6	0.3															0.1			
Caprylic	8:0					6.8	1.9					0.8	1.3												
Capric	10:0				0.1	5.4	1.1					0.5	0.9	0.6								0.1			
Lauric	12:0	0.4				47.7	5.4			0.1	0.2	0.3	0.3	0.1	0.1			0.1	0.2	0.1	0.3	0.2	0.1	0.2	0.6
Tridecylic	13:0																								
Myristic	14:0	2.7	3.6			18.5	1.3			0.3	0.5	1.1	0.5	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	2.6	0.7	0.8	0.6
Myristoleic	14:1																					0.3	0.2		
Pentadanoic	15:0																					0.6	0.3	0.1	
Pentadecenoic	15:1																					0.1			
Palmitic	16:0	6.1	1.5	4.2	1.0	9.1	1.7	11.5	1.7	14.9	2.1	42.5	3.2	4.2	1.1	8.2	1.7	11.6	2.0	6.4	1.8	24.3	2.8	16.5	5.6
Palmitoleic	16:1			0.3	0.3	0.1	0.2	0.2	0.2	1.0	0.5	0.2	0.1	0.1	0.1	0.1		0.2	0.3	0.1	0.1	2.6	1.0	0.9	1.1
Hexadecadienoic	16:2																								
Hexadecatrienoic	16:3																								
Heptadecanoic	17:0			0.1						0.1		0.1		0.1				0.1	0.1	0.1		1.4	0.2	0.1	0.1
Heptadecenoic	17:1			0.1				0.1										0.1				0.6	0.3	0.1	
Stearic	18:0	2.8	0.4	2.0	0.4	2.7	0.7	1.9	0.3	6.1	1.7	4.2	1.1	1.6	0.7	2.5	1.0	3.9	0.8	3.6	1.1	18.2	4.5	7.1	3.9
Oleic	18:1	16.8	3.0	60.4	2.9	6.8	2.1	26.6	2.2	40.4	6.7	41.3	2.9	59.5	7.8	14.2	3.2	23.7	2.4	21.7	5.3	42.2	4.1	44.6	9.3
Linoleic	18:2	17.0	2.3	21.2	1.8	2.1	1.4	58.7	2.8	36.2	6.1	9.5	1.8	21.5	2.8	74.3	8.3	53.8	3.5	66.3	7.6	4.4	2.9	25.1	10.3
Linolenic	18:3	35.6	3.4	9.6	2.1	0.1	0.1	0.6	0.4	0.3	0.2	0.3	0.1	8.4	1.3	0.1	0.1	5.9	2.6	1.5	2.6	0.9	0.7	1.1	1.1
Stearidonic	18:4																					0.4		0.5	
Arachidic	20:0	1.4	1.3	0.7	0.3	0.1	0.1	0.3	0.2	0.2	0.1	0.3	0.1	0.4	0.5	0.1	0.1	0.3	0.3	0.3	0.2	0.2	0.1	0.3	0.1
Gondoic	20:1	14.4	2.8	1.5	0.2	0.0		0.1		0.1		0.1	0.1	2.1	3.0			0.3	0.1	0.2	0.2	0.6	0.2	0.5	0.1
Eicosadiensic	20:2	1.5	0.2	0.1										0.1											
Eicosatrienoic	20:3	0.8																							
Eicosatetraenoic	20:4																								
Eicosapentaenoic	20:5																								
Behenic	22:0	0.9	0.6	0.3	0.1			0.1	0.1	0.2	0.1			0.1		0.3	0.3			0.3	0.2	0.6	0.4	0.1	0.1	0.4	0.2
Erucic	22:1	3.1	0.8	0.5	0.2	0.0	0.0	0.1	0.1	0.1	0.1		0.0	0.5	0.5			0.1	0.1	0.1	0.1		0.1	0.1	0.1
Docosatetraenoic	22:4					0.0																			
Docosapentaenoic	22:5																								
Docosahexaenoic	22:6																								
Lignoceric	24:0	0.7	0.5	0.2	0.1	0.0		0.1	0.1	2.6	3.5		0.1		0.1			0.1	0.1	0.2	0.2			0.2	0.2
Nervonic	24:1	0.2	0.2	0.2		1.0				0.1				0.1	0.1			0.3	0.6					4.4	
Other/Unknown		1.0		2.2				0.3		1.2	1.1	0.9	0.9	4.3	4.4	0.8	0.8	4.1	4.7	0.1		2.0	1.2		
Total		104.1		101.2		101.1		100.2		102.7		101.2		99.9		99.5		100.8		101.2		100.0		103.1	
No. of References		6		14		14		12		20		27		20		9		39		18		16		19	

Dominant species in FAME Composition   Other major species (<= 10%) in FAME composition

is also a consequence of the way in which mean concentration values were determined. The mean values reported in Table III were obtained by averaging only reported non-zero values. In many instances, only a few references reported values for a minor FA in a given profile, while many other references reported nothing for this FA. In such cases, this approach for determining means has the effect of over estimating the concentration of these minor species, and to thereby compute total concentrations that exceed 100%.

Average compositional profiles of biodiesel from the 12 animal fat and vegetable oil feedstocks are shown graphically in Figure 2. (Note: "unknown" values are not included in these graphs.) These depictions provide useful insights into differences among the various biodiesel types. For example, most of the 12 compositions are dominated by C_{18} compounds, while a few have substantial amounts of lighter compounds; especially C_{12} for coconut and C_{16} for palm.

Of the fuels dominated by C_{18}, the relative amounts of saturated (18:0), mono-unsaturated (18:1) and di-unsaturated (18:2) compounds vary considerably. Rapeseed and canola (a close relative of rapeseed) contain mostly 18:1; corn, safflower, soy, and sunflower contain mostly 18:2; jatropha, and yellow grease have more nearly equal amounts of 18:1 and 18:2. Of the 12 profiles shown in Figure 2, camelina contains the highest level of 18:3. Of interest is the reported presence of lignoceric acid (24:0) in jatropha-derived FAME. The mean concentration of 2.6% comes from just two literature values – out of 20 total sources. Thus, this value may be unreliable, though it warrants further investigation, since even 2% of this heavy paraffinic species could lead to concerns about low temperature operability.

As indicated by relatively large standard deviations, the composition of yellow grease is more variable than that of most other feedstocks. The heterogeneous nature of yellow grease has also been noted by Knothe and Steidley. [27] This is expected, because yellow grease is not a well defined, single material, but is composed of used cooking oil from various sources. Hence, yellow grease could resemble corn oil, canola oil, sunflower oil, olive oil, or several other food-grade oils.

2.2 Compositional Profiles of Biodiesel from Algal Lipids

Numerous algal strains have been investigated as potential sources of triglyceride feedstocks for biodiesel production. Due to their rapid growth rates, high lipid contents, tolerance for poor quality water, use in cleaning-up wastewater effluents, and other favorable qualities, interest in developing algal feedstocks for biodiesel continues to increase. [28,29,30,31,32] A comprehensive investigation of algae as a biodiesel feedstock was conducted 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, productivities, and compositional profiles of various algal strains. [33] Recently, NREL and DOE have resumed investigations of algal fuels and have issued a technical roadmap for establishment of a domestic, commercial-scale algae-based biofuels industry. [34,24]

Despite tremendous interest in algal feedstocks for biodiesel, the literature contains relatively few reports of detailed compositional profiles of the triglyceride fractions in algal lipids. It is known that for some algal strains, the FA compositional profiles are highly influenced by specific growth conditions such as nutrient levels, temperatures, and light intensities. [30] This makes it more difficult to define a single compositional profile for algal-based biodiesel, as compared to vegetable oil-based biodiesel. Also, although many different algal materials have been investigated, the exact species is often unknown, or mixed species are used. In addition, there are relatively few instances of the same algal species being characterized by more than one research group.
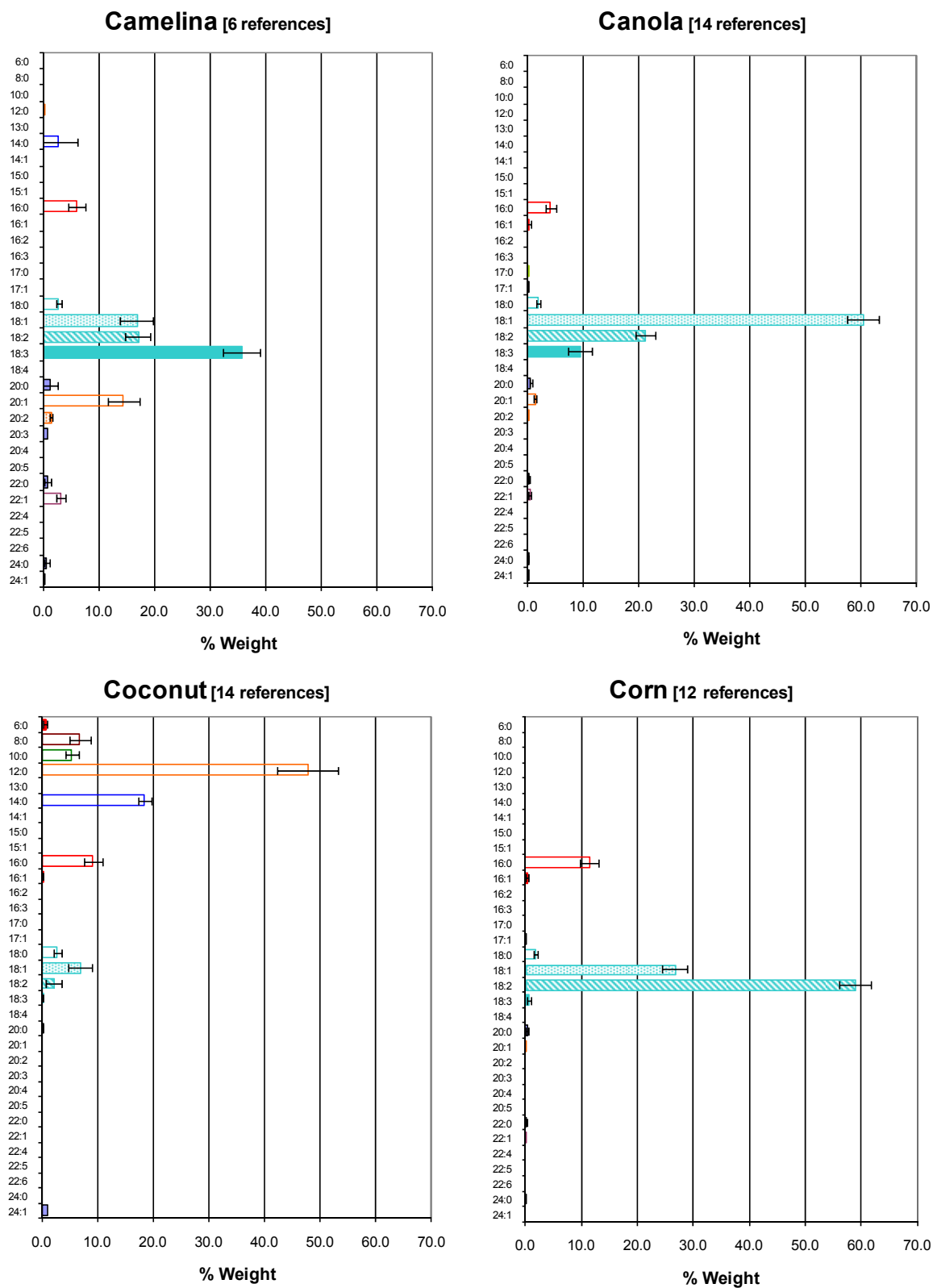
Figure 2a,b.c. Compositional Profiles of Biodiesel from Fats and Oils
(Confidence intervals represent one standard deviation)

Jatropha [20 references]

Palm [27 references]

Rapeseed [20 references]

Safflower [9 references]

(b)

Soy [39 references]

Sunflower [18 references]

Tallow [16 references]

Yellow Grease [19 references]

(c)

41
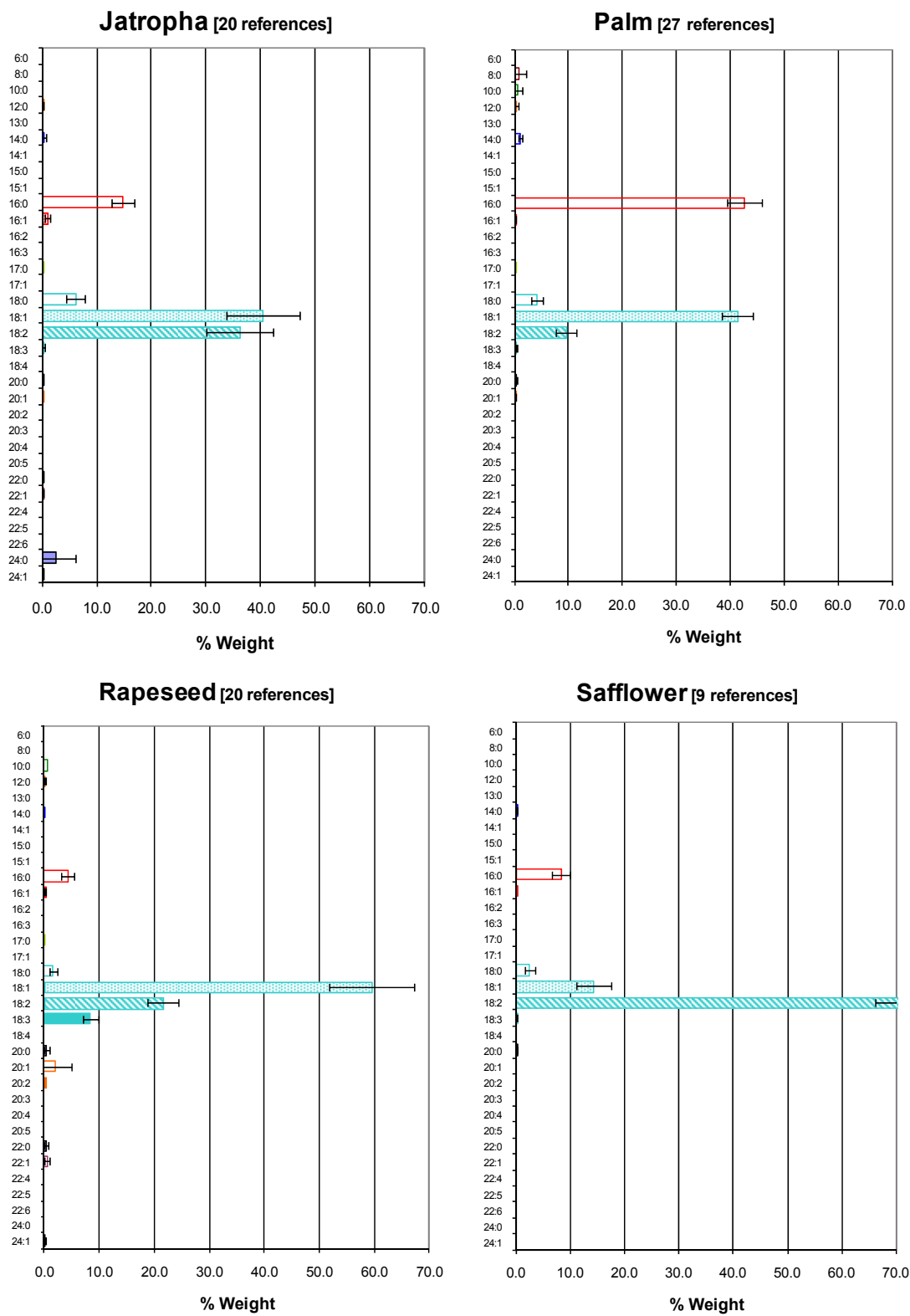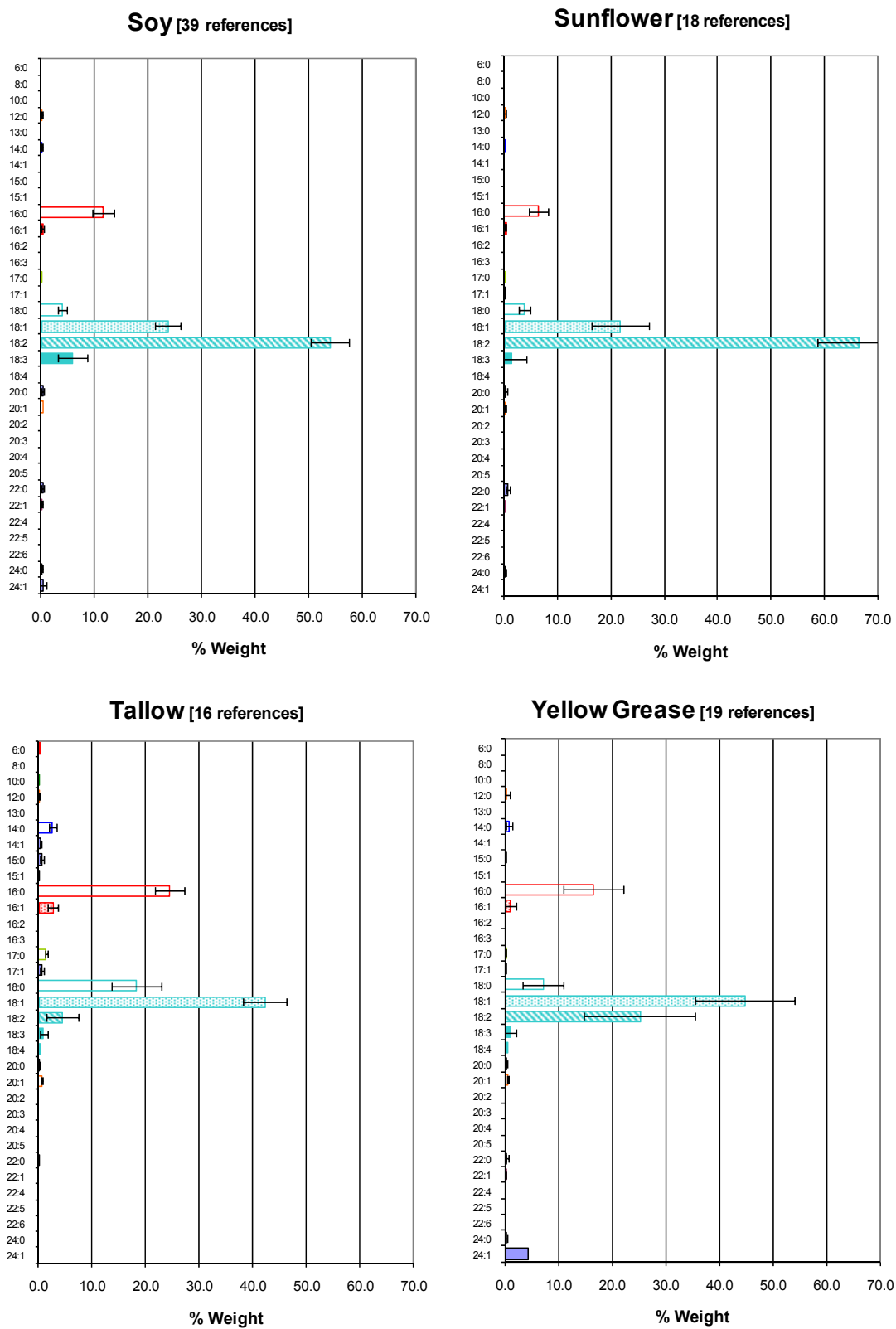
Over 40,000 algal species have been identified, with many more remaining unidentified. [30] Algae are often classified into the following major groupings:

- Cyanobacteria   (Cyanophyceae)
- Green algae   (Chlorophyceae)
- Yellow-green algae   (Xanthophyceae)
- Golden algae   (Chrysophyceae)
- Red algae   (Rhodophyceae)
- Brown algae   (Phaeophyceae)
- Diatoms   (Bacilleriophyceae)
- Pico-plankton   (Eustigmatophyceae)

Most algae that have been investigated as potential biodiesel feedstocks are green algae (Chlorophyceae), although several other types have also been reported. Triacylglycerides are the desired component within algal lipids for use as biodiesel feedstocks. However, these lipids typically also contain lesser amounts of wax esters, sterols, tocopherols, hydrocarbons, and others. Just as with the vegetable oil feedstocks described earlier, triglyceride production within algae varies considerably from one species to the next. For algae, this is typically represented as the total lipid content, expressed as mass percent on a dry basis. As shown in Figure 3, lipid contents vary widely, from less than 10% to over 50%. One reason for the large range of values for each species is that lipid content also varies as a function of growth conditions. However, lipid content alone does not define the total productivity of an algal strain, as productivity is the product of lipid content and algal growth rates. [35]
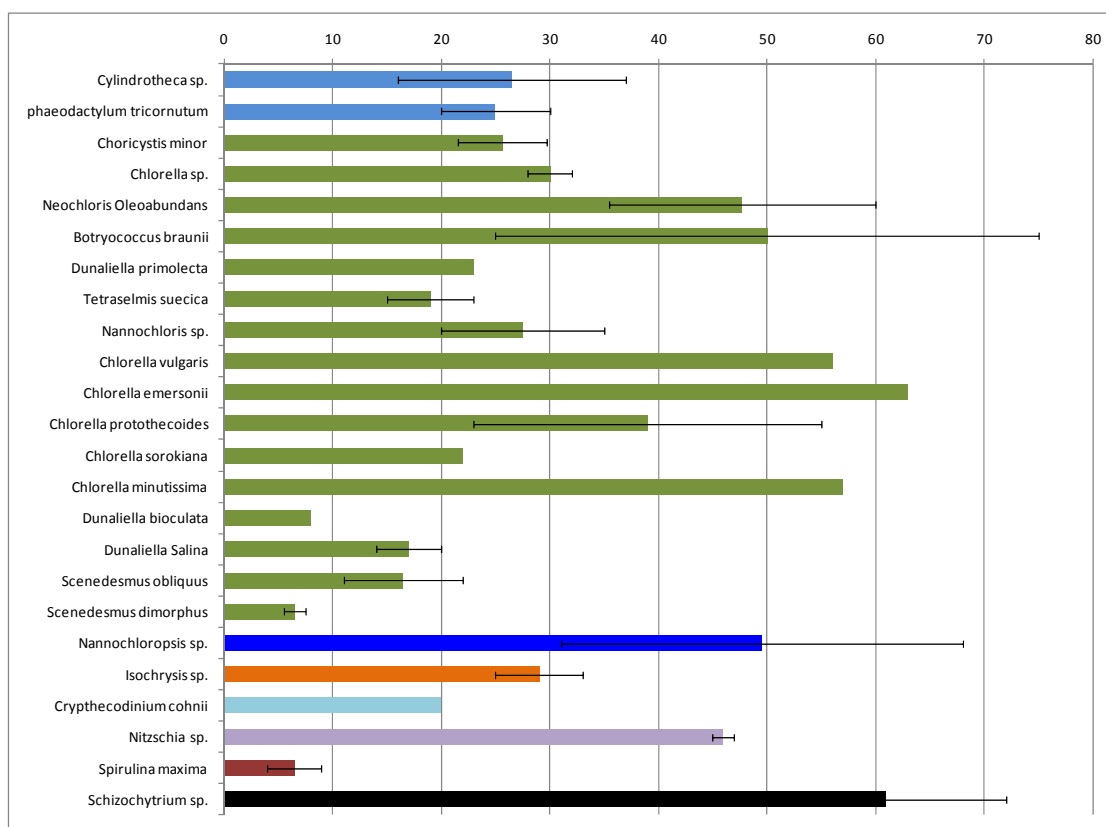
Figure 3. Lipid Contents of Various Algal Species, Wt%.
(Confidence intervals are min. and max. of reported values. Data taken from [30,20,36,31,37])

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Table IV identifies 12 algal species having FA compositional profiles reported in the literature. Average profile data are shown in Table V; individual reported profiles are provided in Appendix V. In several cases, only one or two literature references were found to give the FA profiles; in no case were more than five references found. Consequently, these profiles should be regarded as having high uncertainty – even more so when considering that algal compositions also vary significantly depending upon growth conditions. For these algal FA compositions, no effort was made to identify and eliminate outliers, or to manipulate the data in any other way.

Average compositional profiles of the 12 algal species investigated for this report are shown graphically in Figure 4. Comparison with the vegetable oil profiles in Figure 2 reveals several interesting features. First, although most of these algal species have considerable amounts of C_{16} and C_{18} species, they are not as dominated by these species as are most vegetable oils. Second, some (but not all) algal FA profiles are broader than those of vegetable oils, containing significant amounts of both lighter species (C_{12}-C_{14}) and heavier species (C_{20}-C_{22}). Third, many (but not all) of the algal profiles contain substantial amounts of highly unsaturated species, including FAs with 3-6 double bonds. The implications of this feature with respect to biodiesel properties will be discussed later.

Table IV. Algal Species with Fatty Acid (FA) Profiles Reported in the Literature

Phylum	Genus	Species	Category	References
Bacillariophyta	Chaetoceros	calcitrans	Diatom	Fernandez-Reiriz (1989)
				Volkman (1989)
	Skeletonema	costatum	Diatom	Volkman (1989)
				Zhukova (1994)
	Phaeodactylum	tricornutum	Diatom	Zhukova (1994)
				Fernandez-Reiriz (1989)
Chlorophyta	Chlamydomonas	reinhardtii	Green	Tsuzuki (1990)
	Chlorella	vulgaris	Green	Hu et al (2008)
				Tsuzuki (1990)
				Gouveia (2009)
				Francisco (2009)
	Dunaliella	salina	Green	Zhukova (1994)
	Dunaliella	teriolecta	Green	Volkman (1989)
				Tsuzuki (1990)
				Francisco (2009)
				Zhukova (1994)
				Gouveia (2009)
	Scenedesmes	obliquus	Green	Lopes da Silva (2009)
				Francisco (2009)
				Gouveia (2009)
	Neochloris	oleabundans	Green	Lopes da Silva (2009)
				Gouveia (2009)
Cryptophyta	Chromonas	salina	Cryptomonad	Volkman (1989)
				Zhukova (1994)
Eustigmatophyta	Nannochloropsis	oculata		Zhukova (1994)
Haptophyta	Isochrysis	galbana	Haptophytes	Hu et al (2008)
				Fernandez-Reiriz (1989)

Table V. Fatty Acid Compositional Profiles of Algal Lipids

| | | Bacillariophyta | | | | | | Chlorophyta | | | | | | | | | | | | Cryptophyta | | Eustigmatophyta | | Haptophyta | |
| Fatty Acid | | C. calcitrans | | S. costatum | | P. tricornutum | | C. reinhardtii | | C. vulgaris | | D. salina | | D. teriolecta | | S. obliquus | | N. oleabundans | | C. salina | | N. oculata | | I. galbana | |
Common Name	Abbrev.	mean	dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev	mean	Dev
Capriotic	6:0									0.2				0.1											
Caprylic	8:0									0.6															
Capric	10:0									0.5				0.4		1.0									
Lauric	12:0									2.7		1.5		1.9	2.0	0.5						3.6	3.9		
Tridecylic	13:0									0.7				1.8		0.2									
Myristic	14:0	18.6		14.6	2.6	10.6	5.3	2.3		2.5	1.1	0.6	0.1	1.0	0.6	0.9	0.9	1.9	1.7	20.4	14.8	3.7	0.2	10.6	5.3
Myristoleic	14:1			0.4	0.0					0.9		0.4	0.4	0.7	0.8	21.7		0.4		0.3		0.2			
Pentadanoic	15:0			2.7						31.8		1.9		9.4	11.9	2.3		1.4		3.5	4.2	1.8			
Pentadecenoic	15:1									2.4				2.4		6.2									
Palmitic	16:0	26.3		12.4	4.2	13.8	2.5	32.4		17.4	10.6	19.4	2.3	13.2	9.7	11.6	14.4	36.3	33.2	16.7	2.8	24.9	10.0	13.8	2.5
Palmitoleic	16:1	27.5		22.8	4.5	9.8	10.3	1.7		3.1	2.3	1.7	1.1	5.5	4.5	5.6	0.6	2.5	0.9	1.8	0.6	23.3	3.8	9.8	10.3
Hexadecadienoic	16:2			4.1	2.1			1.6		8.1	5.6	1.5		2.7	0.6	3.2	1.2	2.1	0.6	0.7		0.8			
Hexadecatrienoic	16:3			10.2	0.2			2.1		2.6	1.6	7.2	4.4	2.8	1.7	0.7		1.0				0.6			
Heptadecanoic	17:0			0.3						3.9				1.4		20.4		11.7		1.1	0.4	1.1			
Heptadecenoic	17:1									31.6				4.1		1.2		1.0							
Stearic	18:0	2.6		1.8	0.6	1.2	0.1			1.0	0.4	1.5		2.6	3.3	10.0	13.5	5.0	5.3	2.2	0.9	2.1	1.5	1.2	0.1
Oleic	18:1	4.5		2.9	0.4	15.7	8.3	17.7		9.2	4.4	5.3	2.6	5.7	4.3	9.5	11.8	23.4	11.4	12.8	6.8	5.8	1.8	15.7	8.3
Linoleic	18:2	0.8		1.4	0.3	4.4	2.4	10.8		20.7	19.6	6.2	0.1	14.2	9.6	17.5	6.0	10.2	4.0	9.3	10.0	3.6	3.3	4.4	2.4
Linolenic	18:3			0.9	0.9	2.9	2.0	21.6		14.3	12.0	38.7	1.0	35.0	6.1	1.9	2.6	10.0	10.6	8.5	2.8	3.8	4.1	2.9	2.0
Stearidonic	18:4			2.4	0.8	13.8	6.8					0.7		1.3		0.2		2.1		11.4	16.4			13.8	6.8
Arachidic	20:0									1.5	2.0					2.0		2.1							
Gondoic	20:1									0.9								2.5		0.2	0.1				
Eicosadiensic	20:2			0.2								0.1				0.4						0.1			
Eicosatrienoic	20:3									0.8												0.4	0.1		
Eicosatetraenoic	20:4			1.4		0.5				0.4	0.2			0.3	0.0					1.8	1.4	4.5	0.8	0.5	
Eicosapentaenoic	20:5	6.7		14.2	1.7	13.1	17.7			0.5		0.1		0.4						5.0	6.9	27.6	10.8	13.1	17.7
Behenic	22:0																								
Erucic	22:1																								
Docosatetraenoic	22:4																								
Docosapentaenoic	22:5					1.2														0.1				1.2	
Docosahexaenoic	22:6	0.6		2.1	0.4	14.4	5.4			0.5										2.9	3.7			14.4	5.4
Lignoceric	24:0																								
Nervonic	24:1					2.3																		2.3	
Total																									
No. of References		1		2		5		1		4		2		4		2		3		3		3		3	

C. calcitrans [1 references]

S. costatum [2 references]

P. tricornutum [5 references]

C. reinhardtii [1 references]
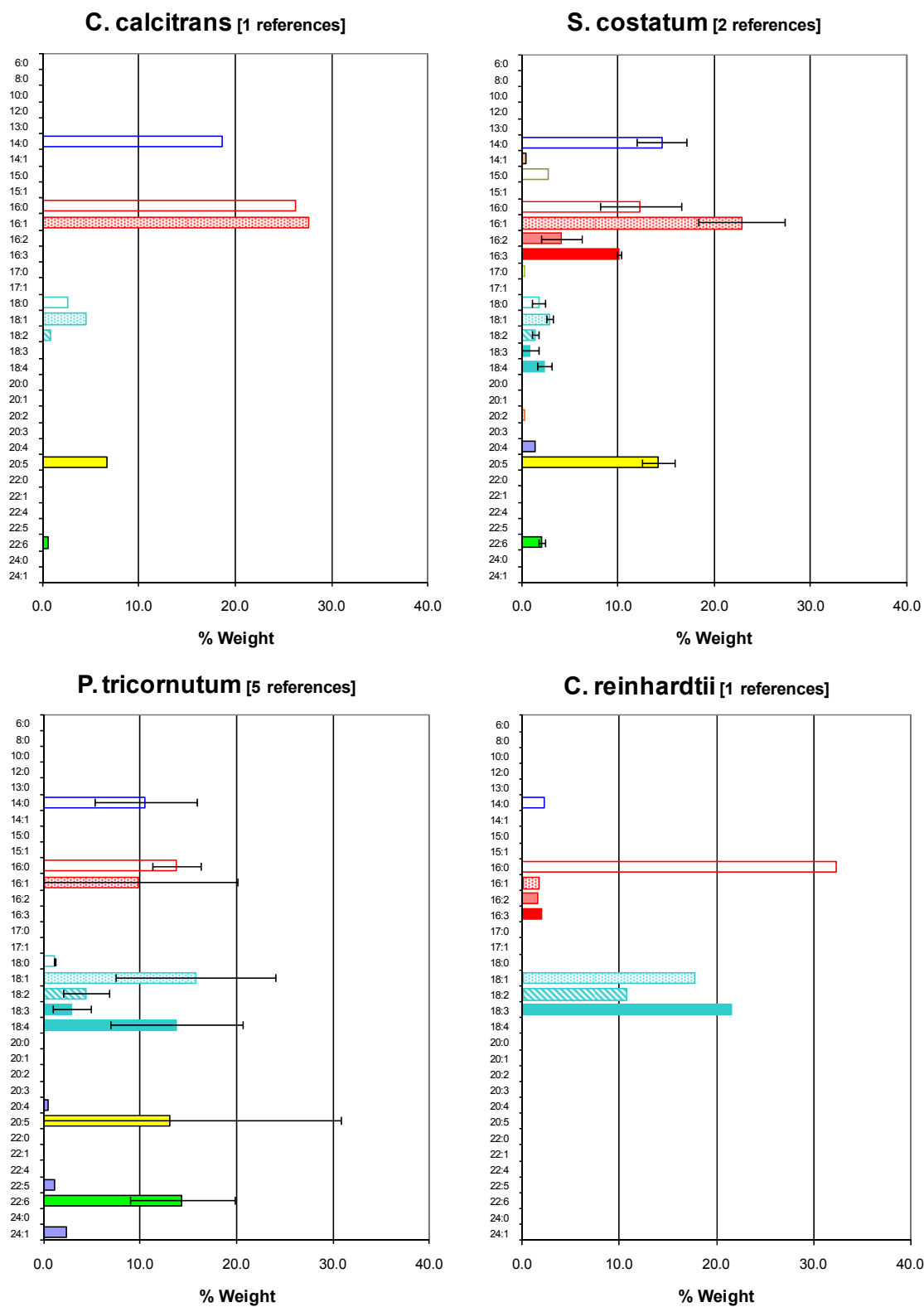
(a)

Figure 4a,b,c. Fatty Acid Compositional Profiles from Algal Lipids
(Confidence intervals represent one standard deviation)

C. vulgaris [4 references]

D. salina [2 references]

D. teriolecta [4 references]

S. obliquus [2 references]
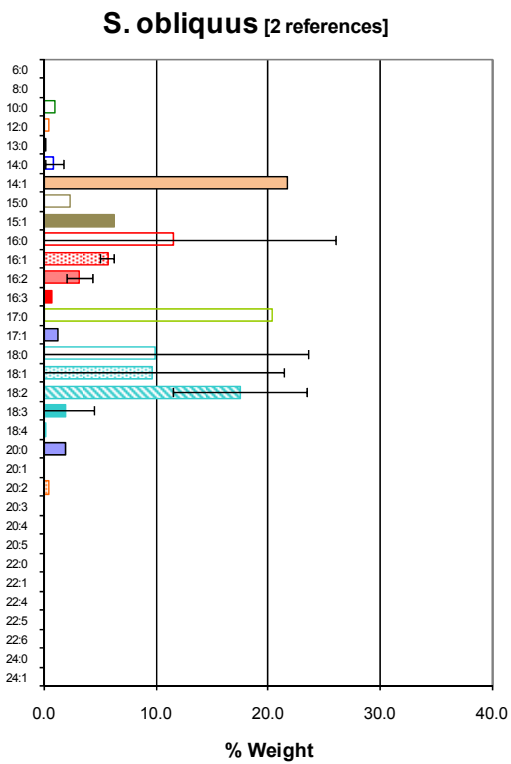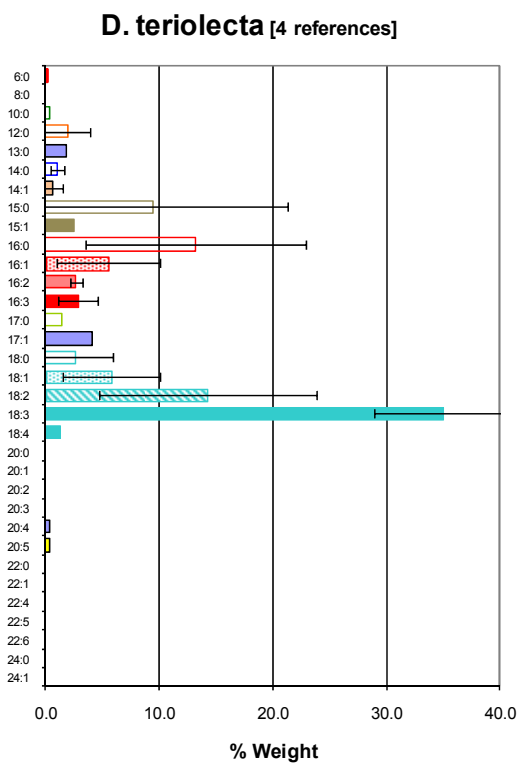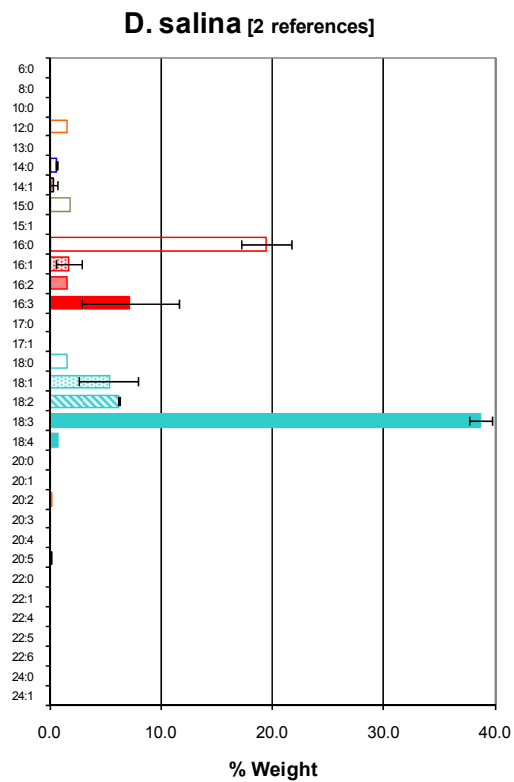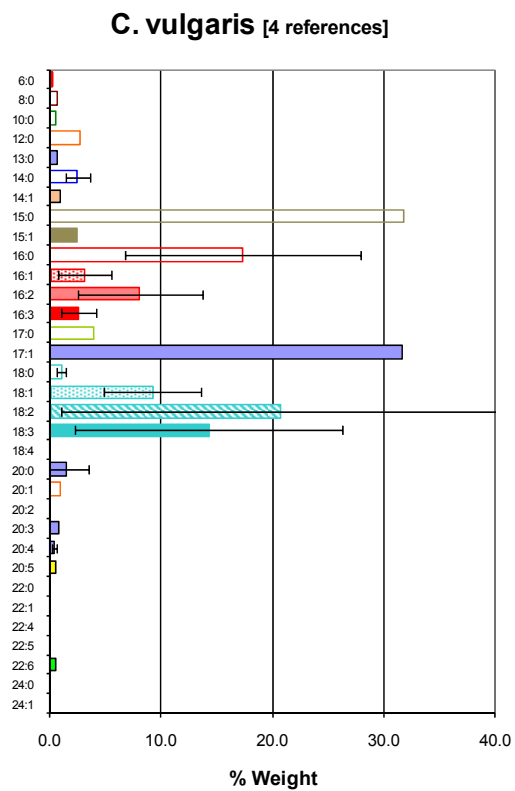
(b)

N. oleabundans [3 references]
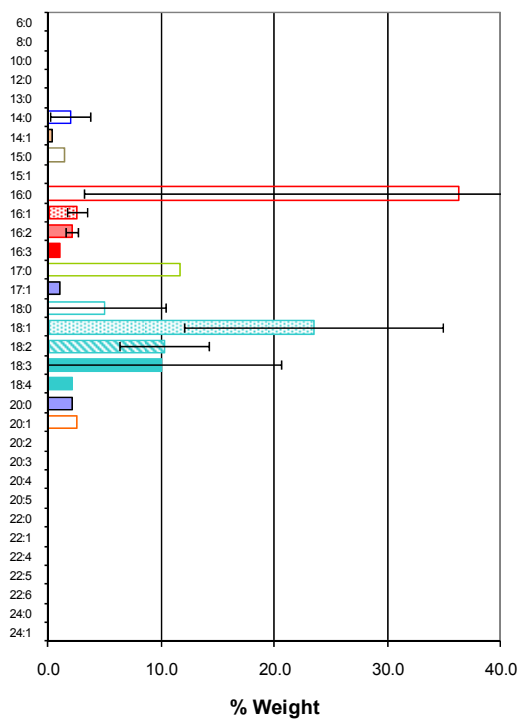
C. salina [3 references]
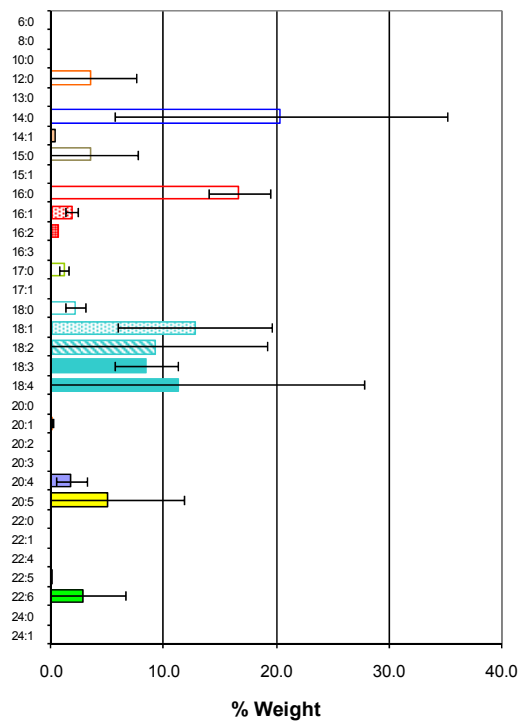
N. oculata [3 references]
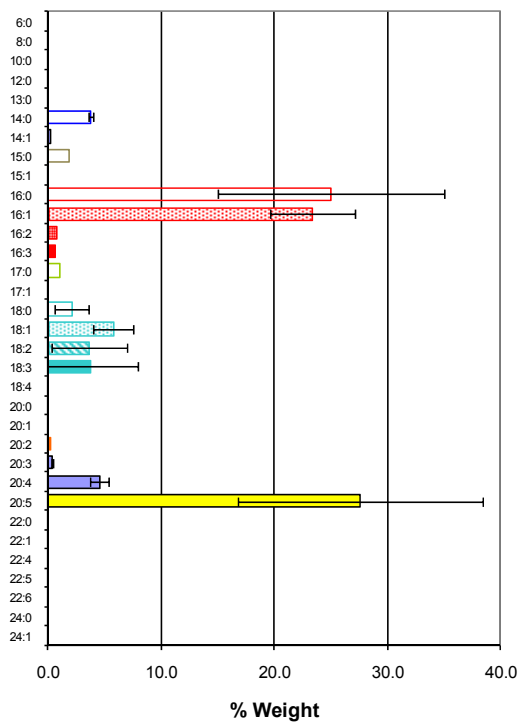
I. galbana [3 references]
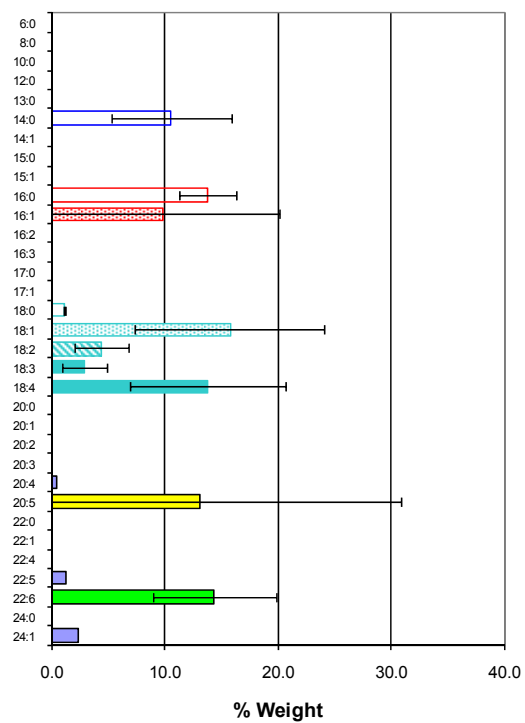
(c)

47

3.   BIODIESEL PROPERTIES

The physical and chemical properties of biodiesel are determined by the compositional profiles described above. Biodiesel properties can vary substantially from one feedstock to the next. Specific variations with feedstock are discussed below in greater detail. However, it is also useful to briefly compare a few critical properties of biodiesel fuels as a class, with the properties of ULSD. Table VI (reproduced from the earlier AVFL-17 report [4]) provides such a summary comparison. For completeness, typical properties of renewable diesel are also included. (A thorough comparison of biodiesel and renewable diesel with respect to production, properties, and impacts has recently been published.[38]) The property values shown in Table VI were derived by compositing information from several literature sources. [39,40,41,42,43,44,45,46] The properties of individual fuels can vary from those shown here.

Table VI. Typical Properties of Biodiesel Compared to ULSD and Renewable Diesel

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

Because of its considerable oxygen content (typically 11%), 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.

Renewable diesel consists mainly of paraffinic hydrocarbons, usually dominated by odd carbon numbers. [40,39,47] (Depending upon process variables, even carbon number hydrocarbons can also be produced.) While some renewable diesel fuels contain primarily straight-chain, normal paraffins, others contain appreciable amounts of branched paraffins. As a consequence of their high paraffinic content, renewable diesel fuels typically have cetane numbers much higher than biodiesel. On a mass basis, the energy content of renewable diesel is higher than biodiesel (similar to ULSD); on a volumetric basis, the energy content of biodiesel and renewable diesel are very similar.

When reviewing the properties of biodiesel prepared from different feedstocks, it is useful to bear in mind the standard specifications that have been established by various fuel standard-setting organizations. 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 D6751, [11] as well as for biodiesel blends of B6 to B20 in petroleum diesel, called ASTM D7467. [48] Blends of B5 and below are permitted under the standard specifications for No. 2 diesel fuel, ASTM D975. [49]

Thus far, the CEN has only established standard specifications for B100, called EN 14214, [50,51] but not for mid-level blends such as B20. The European standard specifications for conventional No. 2 diesel fuel (EN 590) permit blends of B7 and below; and deliberations are now underway to allow an increase up to blends of B10. [46]. Table VII provides a side-by-side listing of specifications for biodiesel blendstock (B100: ASTM and CEN) and mid-level biodiesel blends (B6-B20; ASTM only). For each specification, both the limits and the methods are shown.

Table VII. U.S. and European Specifications for Biodiesel (B100) and Biodiesel Blends

Property	Biodiesel Blendstock (B100)				B6 – B20 Blends	
	U.S. (ASTM D6751-08)		Europe (EN 14214)		U.S. (ASTM D7467-08)	
	Limits	Method	Limits	Method	Limits	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		
Kinematic Viscosity @ 40° C (mm^2/s)	1.9-6.0	D 445	3.5-5.0	EN 3104/3105	1.9-4.1	D 445
Flash Point, Closed Cup (°C, min.)	93	D 93	101	EN 3679	52	D 93
Methanol (wt.%, max.)	0.20 [A]	EN 14110	0.20	EN 14110		
Cetane No. (min.)	47	D 613	51	EN 5165	40	D 613
Cetane Index (min.)					[H]	
Cloud Point (°C)	Report [D]	D 2500	Country Specific [D]		Report [D]	D 2500
Sulfated Ash (wt.%, max.)	0.020	D 874	0.020	EN 3987		
Total Ash (wt.%, max.)					0.01	D 482
Gp I metals Na + K (mg/kg, max.)	5.0	EN 14538	5.0	EN 14108/14109		
Gp II Metals Ca + Mg (mg/kg, max.)	5.0	EN 14538	5.0	EN 14538		
Total Sulfur (ppm, max.)	15 [B]	D 5453	10	EN 20846	15	D 5453
Phosphorous (ppm, max.)	10	D 4951	4	EN 14107		
Acid No. (mg KOH/g, max.)	0.50	D 664	0.50	EN 14104	0.3	D 664
Carbon Residue (wt. %, max)	0.05	D 4530	0.30 [E]	EN 10370	0.35 [E]	D 524
Free Glycerin (wt.%, max.)	0.02	D 6584	0.02	EN 14105/14106		
Total Glycerin (wt.%, max.)	0.24	D 6584	0.25	EN 14105		
Mono Glyceride (wt.%, max)			0.80	EN 14105		
Diglyceride (wt.%, max)			0.20	EN 14105		
Triglyceride (wt.%, max)			0.20	EN 14105		
Distillation (T-90 °C, max.)	360 [C]	D 1160			343	D 86
Copper strip corrosion (3-hr. at 50° C, max.)	No. 3	D 130	No. 1	EN 2160	No. 3	D 130
Oxidation Stability (hrs @ 110°C, min)	3.0	EN 14112	6.0	EN 14112	6	EN 14112
Linolenic acid methyl ester (wt.%, max)			12.0	EN 14103		
Polyunsaturated acid methyl esters (wt.%, max)			1.0	prEN 15799		
Ester Content (wt.%, min)			96.5	EN 14103	6-20 vol.%	D 7371
Iodine Value (g I$_2$/100g, max.)			120	EN 14111		
Density (kg/m^3)			860-900	EN 3675		
Lubricity @ 60°C, WSD, microns (max.)					520	D 6079
Cold Soak Filterability (seconds, max.)	360 [F]	D 7501				

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 (in units of µg/g), but not sediment
H   Calculated cetane index approximation, Test Method D 4737, is not applicable to biodiesel blends

3.1 Properties of Biodiesel from Fats and Oils

Table VIII summarizes several of the most important physical/chemical properties of biodiesel (FAME) derived from the same 12 feedstocks whose compositional profiles were discussed above. These data were obtained using a similar process as with the fatty acid (FA) profile data. Numerous literature sources were reviewed, as documented in the tables of Appendix VI. The number of references for a given FAME varied from 4 (for safflower) to 59 (for soy).

FAME property values reported by different authors vary considerably. As with the FA compositional profiles, this variation in properties is largely attributed to use of different analytical methods and different skill levels in applying these methods. Additional sources of variability include the chemical process used to produce the FAME, the clean-up process used to purify raw FAME, and the storage time (and conditions) prior to analysis.

The oxidative stability of FAME is a critical in-use property of biodiesel, but was not considered in this summary of fuel properties because it is influenced greatly by the FAME clean-up and storage practices employed. In addition, many of the biodiesel samples contained anti-oxidant additives, resulting in a modification of the inherent stability of the FAME material. There are several other FAME properties for which specifications have been established, but that also depend largely upon manufacturing and handling practices, rather than being inherent properties of FAME itself. These include water and sediment, methanol content, ash, metals, acid number, glycerine content, and cold soak filterability. Thus, these properties are not included in the summary Table VIII, or in the tables of Appendix VI.

Important properties that are directly related to FAME itself, and are reported frequently in the literature, include viscosity, cetane number, cloud point, pour point, cold filter plugging point, specific gravity, flash point, iodine value, and heating value. These properties are all included in the individual FAME tables of Appendix VI and the summary Table VIII. In addition, these tables include data for cetane index (CI), which was reported by many authors, usually without indicating the formula that was used in the calculation. Although CI is commonly used to approximate the cetane number for petroleum mid-distillate fuels, a reliable method to calculate CI for biodiesel has not been developed. As shown below, two different formulas for calculating CI (for petroleum distillates) are defined in ASTM specifications: D976 and D4737.

ASTM D976:

$$CI = 454.74 - 1641.416\,D + 774.74\,D^2 - 0.554\,B + 97.803\,(\log B)^2$$

Where:
D = density at 15°C (g/mL)
B = mid-boiling temperature, T_{50} (°C)

ASTM D4737:

$$CI = 45.2 + (0.0892)(T_{10N}) + [0.131 + (0.901)B][T_{50N}] + [0.0523 - (0.420)B][T_{90N}]$$
$$+ [0.00049][T_{10N}^2 - (T_{90N})^2] + 107B + 60B^2$$

Where:
D = density at 15°C (g/mL)
$B = [e^{(-3.5)(DN)}] - 1$
$DN = D - 0.85$
$T_{10N} = T_{10} - 215$ (°C)
$T_{50N} = T_{50} - 260$ (°C)
$T_{90N} = T_{90} - 310$ (°C)

Table VIII: Physical / Chemical Properties of Biodiesel (FAME) from Fats and Oils

Property	Camelina mean	Camelina dev	Canola mean	Canola dev	Coconut mean	Coconut dev	Corn mean	Corn dev	Jatropha mean	Jatropha dev	Palm mean	Palm dev	Rapeseed mean	Rapeseed dev	Safflower mean	Safflower dev	Soy mean	Soy dev	Sunflower mean	Sunflower dev	Tallow mean	Tallow dev	Yellow Grease mean	Yellow Grease dev
Sulfur Content, ppm	2	2	2	0	3	1	4	1	5	6	2	2	4	3	ND		2	2	2	3	7	8	5	5
Kinematic Viscosity @ 40 °C, mm²/s	3.80	0.55	4.38	0.27	2.75	0.24	4.19	0.33	4.75	0.58	4.61	0.56	4.50	0.35	4.14	0.13	4.26	0.39	4.42	0.26	4.69	0.44	4.80	0.48
Cloud Point, °C	3	1	-2	1	-3	3	-3		5	3	14	2	-3	2	-4	2	0	2	2	1	13	2	8	5
Pour Point, °C	-7	3	-6	3	-9	5	-2	2	0	5	13	2	-10	3	-7	1	-4	3	-2	2	10	3	3	7
CFPP, °C	-3	2	-9	4	-5	1	-8	6	ND		9	5	-12	6	-6		-4	2	-2	1	13	2	1	5
Flash Point, °C	136		153	29	113	6	171	16	152	20	163	17	169	16	174	7	159	18	175	9	124	35	161	22
Cetane No.	50.4	1.6	53.7	1.5	59.3	9.7	55.7	2.9	55.7	3.0	61.9	3.6	53.7	2.9	51.1	1.8	51.3	4.6	51.1	3.2	58.9	2.1	56.9	4.2
Cetane Index*	ND		61.5		ND		60.9		ND		50.5	4.4	54.7	5.0	ND		52.3	5.7	55.0	8.4	59.1		48.5	
Iodine Value	152.8	2.5	108.8	1.3	18.5	16.3	101.0		109.5		54.0	6.1	116.1	6.7	141.0		125.5	5.4	128.7	4.6	65.9	15.6	88.9	16.2
Specific Gravity	0.882	0.007	0.883	0.003	0.874	0.001	0.883	0.005	0.876	0.009	0.873	0.008	0.879	0.010	0.879	0.012	0.882	0.007	0.878	0.011	0.878	0.006	0.879	0.010
Lower Heating Value, MJ/Kg	ND		38.9	1.6	35.2		39.9		37.7		37.3	2.3	37.6	1.6	ND		37.0	1.9	35.3	2.1	37.2	0.2	37.6	1.6
Higher Heating Value, MJ/Kg	45.2		41.3	3.1	38.1		43.1	2.7	40.7	1.5	40.6	1.5	41.1	2.3	42.2	2.7	39.7	0.8	40.6	2.4	39.7	0.2	39.4	1.1
Avg. Chain Length	19.10		18.20		13.40		17.80		18.30		17.20		17.90		17.80		17.90		18.10		17.30		18.50	
Avg. Unsaturation	1.81		1.34		0.12		1.46		1.15		0.62		1.31		1.63		1.50		1.59		0.59		1.06	
No. of References	7		15		7		6		23		44		39		4		59		20		12		37	

☐ = No Data found in literature

* = No accepted method for determining cetane index of biodiesel

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Both ASTM formulas for CI are based upon the fuel's density (determined by ASTM D1298) and distillation properties (determined by ASTM D86). These properties are quite different for biodiesel as compared to petroleum diesel. Because of this, the ASTM standard for biodiesel blends (ASTM D7467) includes this cautionary statement: "Calculated cetane index approximation, Test Method D4737, is not applicable to biodiesel blends." CI values have been included in this assessment because they are so commonly reported in the literature, even though there is no accepted method for their determination. Furthermore, CI values are included here to illustrate their lack of correlation with cetane numbers, thus highlighting the unreliability of CI for biodiesel.

Our approach to handling the literature-reported property data was similar to that described above for the FA profile data. Initially, all reported values were accepted, with no *a priori* judgment about data validity. From this raw data, a mean and standard deviation were computed for each FAME. More careful inspection of the data was then conducted, especially for values that were greatly different from the mean. In several cases, viscosity values were found to have been determined at temperatures other than the standard of 40°C. As illustrated in Figure 5, the viscosity of biodiesel and biodiesel blends varies greatly with temperature. Because of this, viscosity values determined at non-standard temperature conditions were not used in determining means and standard deviations.
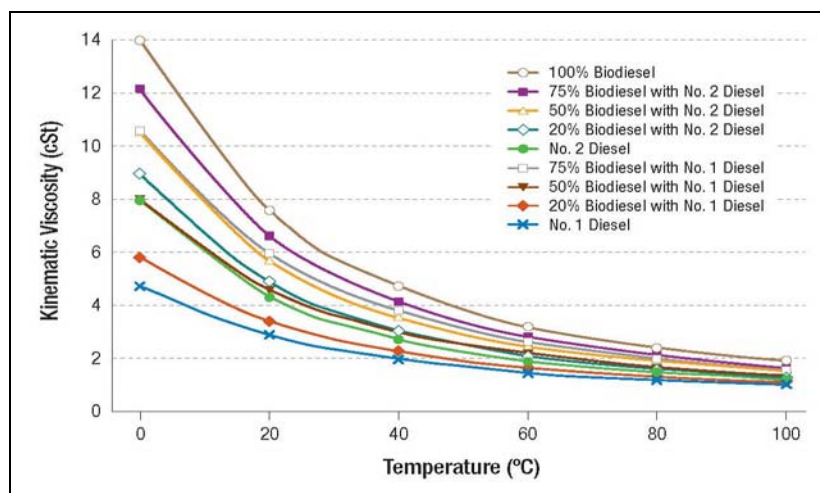
Figure 5. Effect of Temperature on Kinematic Viscosity of Biodiesel and Biodiesel Blends
(taken from NREL's Biodiesel Handling and Use Guide [45])

Sulfur values also required careful assessment. Many sources reported values using older analytical methods meant for conventional diesel fuel, having sulfur levels of 500 ppm or higher. In such cases, results were often reported as < 0.05% (or similar value). These relatively insensitive methods are not appropriate for ULSD or biodiesel. Therefore, for this review, the authors included only sulfur values determined by ASTM D5453 (or equivalent method), which is reliable in measuring ppm levels of sulfur.

Energy content is another important in-use property of FAME, though there is no specification for this in either U.S. or European biodiesel standards. Nevertheless, many authors reported values for energy content – although there is much inconsistency in the metrics used. For example, lower heating value (LHV), higher heating value (HHV), gross energy content, and net energy content were all reported – often without a clear definition of how the measurements were made. In some references, the specific metric being reported was not indicated. In these cases, the authors used their judgment to assign the values as either LHV or HHV. The detailed data tables in Appendix VI indicate (with shaded cells) where such judgments were applied. Shading is also used to highlight outlier values (for all properties) that were not used in calculating means and standard deviations.

Two other "properties" of biodiesel shown in Table VIII were calculated based upon the average compositional profiles of the 12 FAME types: (1) average chain length and (2) average degree of unsaturation. Average chain length was computed by multiplying the mass fraction of each FA constituent times its associated carbon number, then summing over the entire profile. Similarly, average degree of unsaturation was computed by multiplying the mass fraction of each FA constituent times the associated number of carbon-carbon double bonds, then summing over the entire profile.

The average properties of the 12 biodiesel types considered are shown graphically in Figure 6, along with the confidence intervals of ± 1 standard deviation. These depictions provide insights into differences and similarities among the biodiesel fuels. For example, all 12 biodiesel types have very low sulfur contents, with no significant differences among them. All these biodiesels are well below the sulfur specification maximum in ASTM D6751 (15 ppm) and EN 14214 (10 ppm).

3.1.1   Kinetic Viscosity

The kinematic viscosity graph in Figure 6a shows that 10 of the 12 biodiesel types fall within a narrow range of 4-5 mm^2/s. Biodiesel from camelina has slightly lower viscosity at 3.8 mm^2/s, while coconut-derived biodiesel is substantially lower, at 2.75 mm^2/s. The ASTM D6751 viscosity specification of 1.9-6.0 mm^2/s is satisfied by all 12 biodiesels. (These ASTM limits are not shown in Figure 6a as they are "off-scale.") The more restrictive EN 14214 specification of 3.5-5.0 mm^2/s would exclude biodiesel from coconut oil.

3.1.2   Specific Gravity

Specific gravity varied within a narrow range of 0.873 to 0.883 for all 12 biodiesel types shown in Figure 6a. Palm-derived and coconut-derived FAME had the lowest specific gravity values of 0.873 and 0.874, respectively. The EN 14214 standard includes a density specification of 860-900 kg/m^3. (Note: specific gravity and density are used interchangeably in this report.) Biodiesel produced from all 12 of these feedstocks would meet this specification. The ASTM D6751 standard does not include a specification for density.

3.1.3   Cold Flow Properties

The three low temperature properties plotted in Figure 6b [cloud point (CP), pour point (PP), and cold filter plugging point (CFPP)] show very similar patterns across the sets of 12 biodiesel types. In each case, biodiesel from palm oil and tallow show the poorest performance (highest temperature points), while biodiesel from rapeseed generally shows the best performance (lowest temperature points). Because of large seasonal and geographic temperature variability, neither the U.S. nor European biodiesel standards have firm specifications for these low temperature properties, though they are among the most important properties in determining the suitability of biodiesel fuels in-use.

3.1.4   Flash Point

The flash point values shown in Figure 6c are well above the minimum specifications in the U.S. (93°C) and European (101°C) standards. The coconut-derived biodiesel has a significantly lower flash point than the other biodiesel types shown here, although it is still within the standard specifications. The main purpose of the flash point specification is to ensure that the manufactured FAME has been sufficiently purified by removal of excess methanol. Even small amounts of residual methanol in FAME will cause a significantly depressed flash point. Such methanol contamination was likely in a few literature-reported flash point values shown in the tables of Appendix VI. In several cases, these unusually low flash point values were eliminated from the database as being outliers (see shading in the appendix tables).
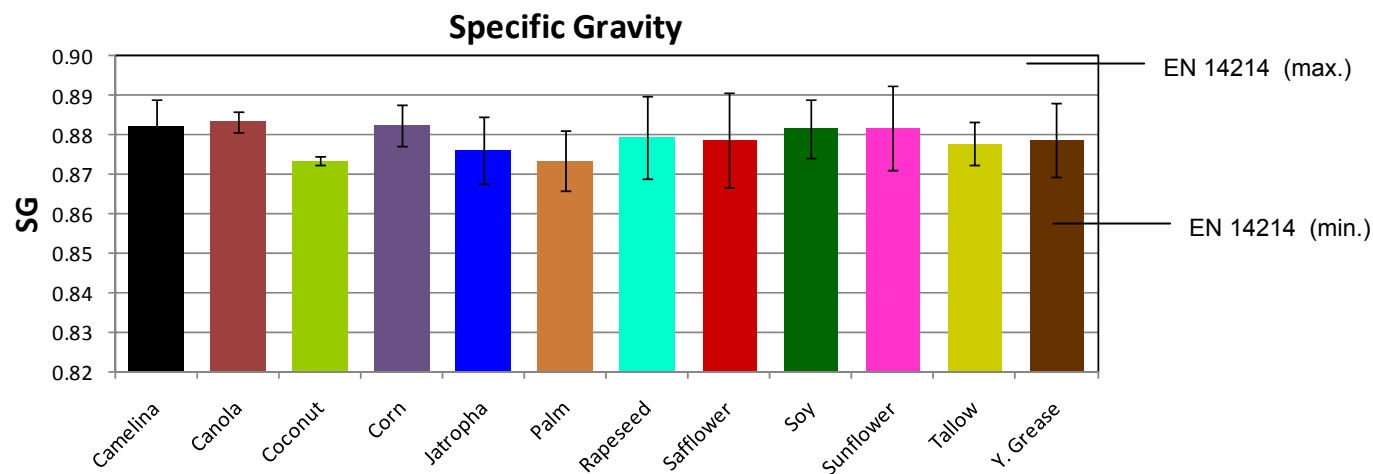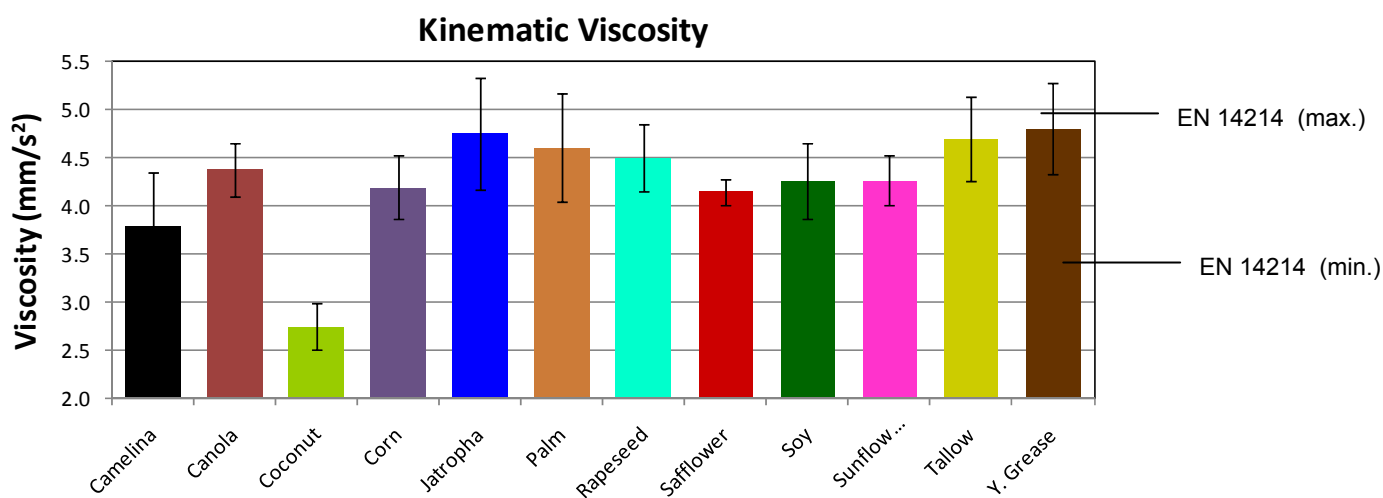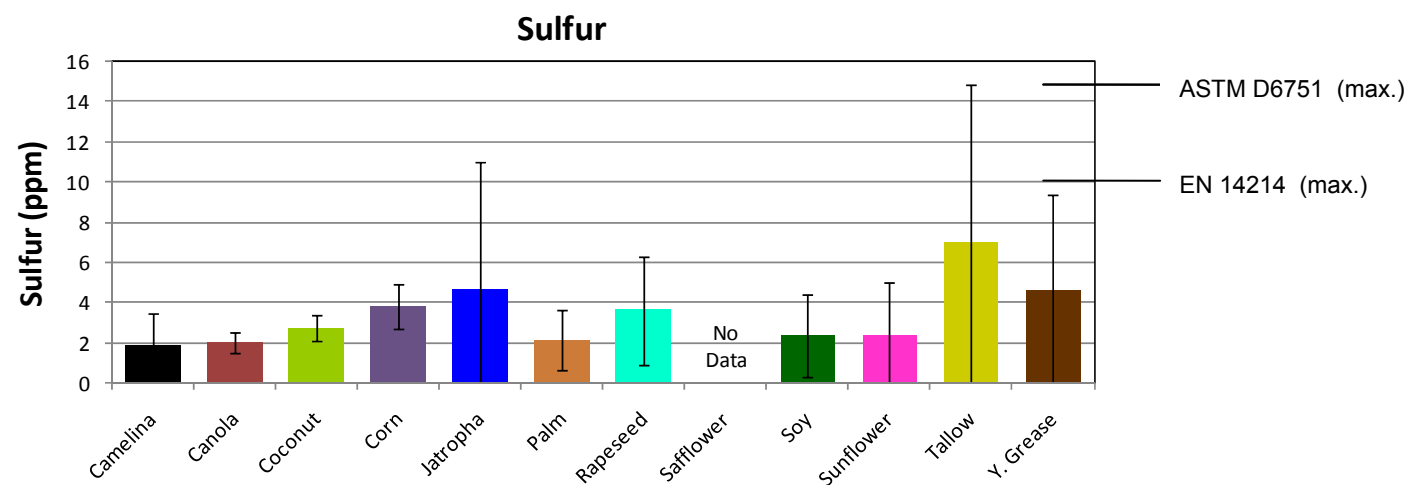
Figure 6a,b,c,d. Average Physical / Chemical Properties of Biodiesel (FAME) from Fats and Oils
(Confidence intervals represent one standard deviation)

Cloud Point

Pour Point

Cold Filter Plugging Point (CFPP)

(b)

55

(c)

Higher Heating Value

Chain Length of Average Profile

Degree of Unsaturation of Average Profile
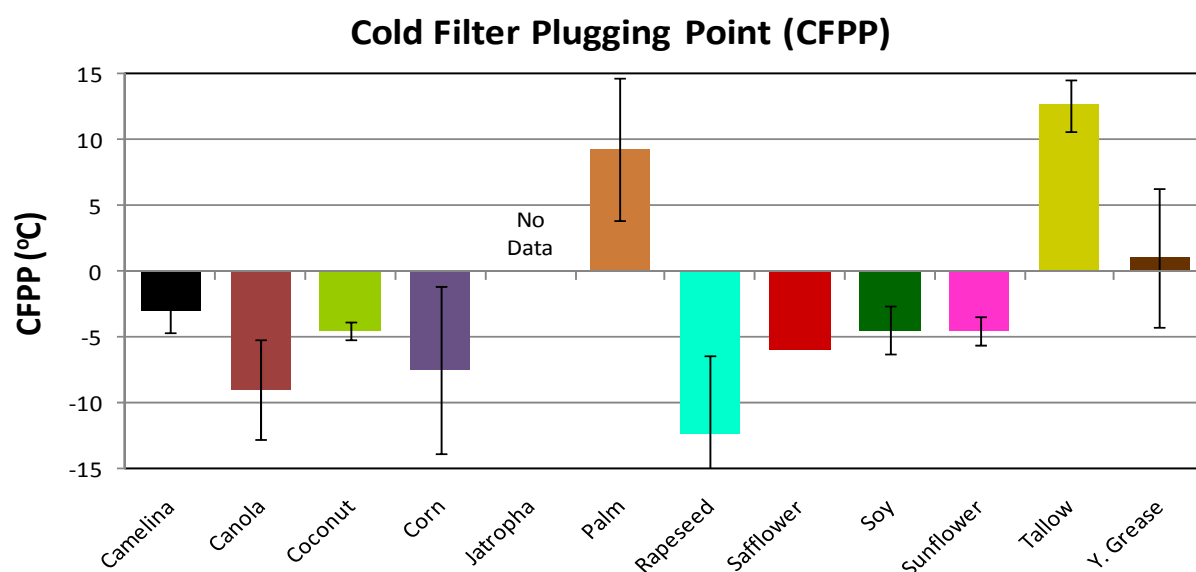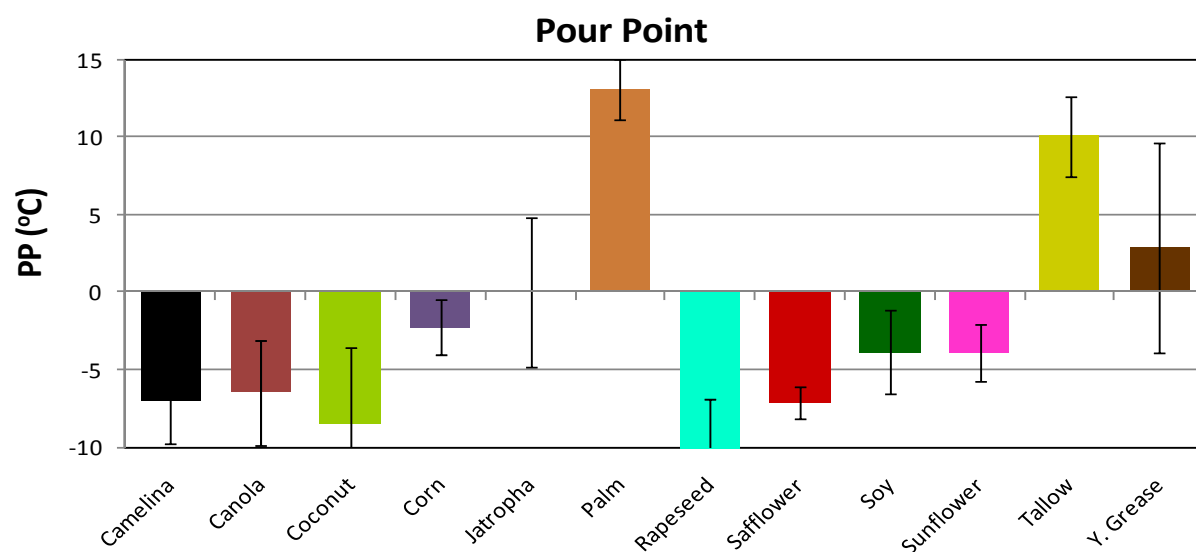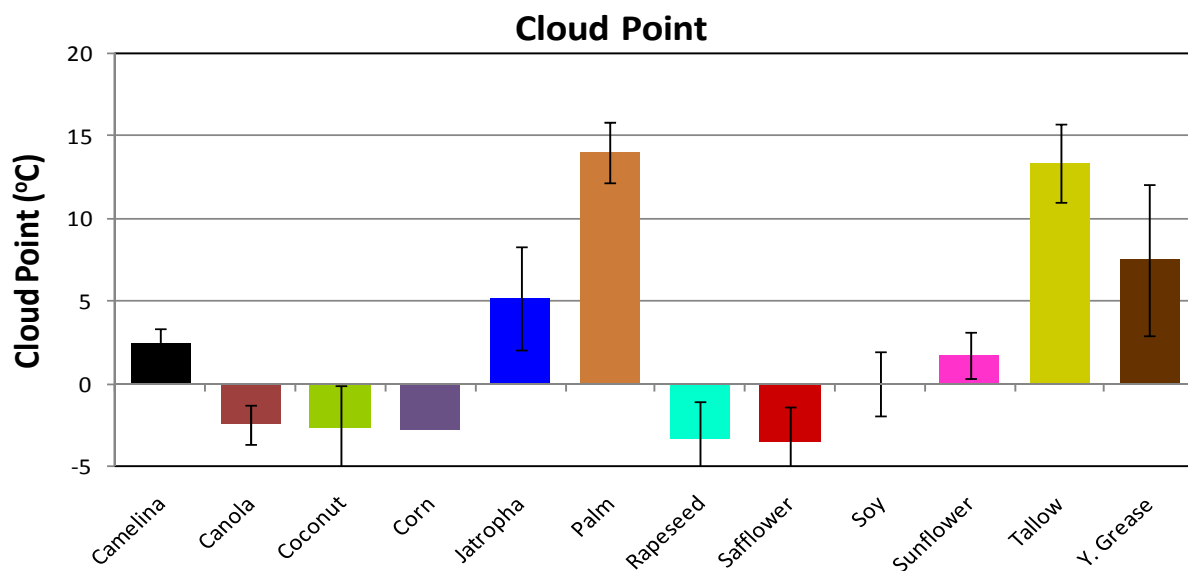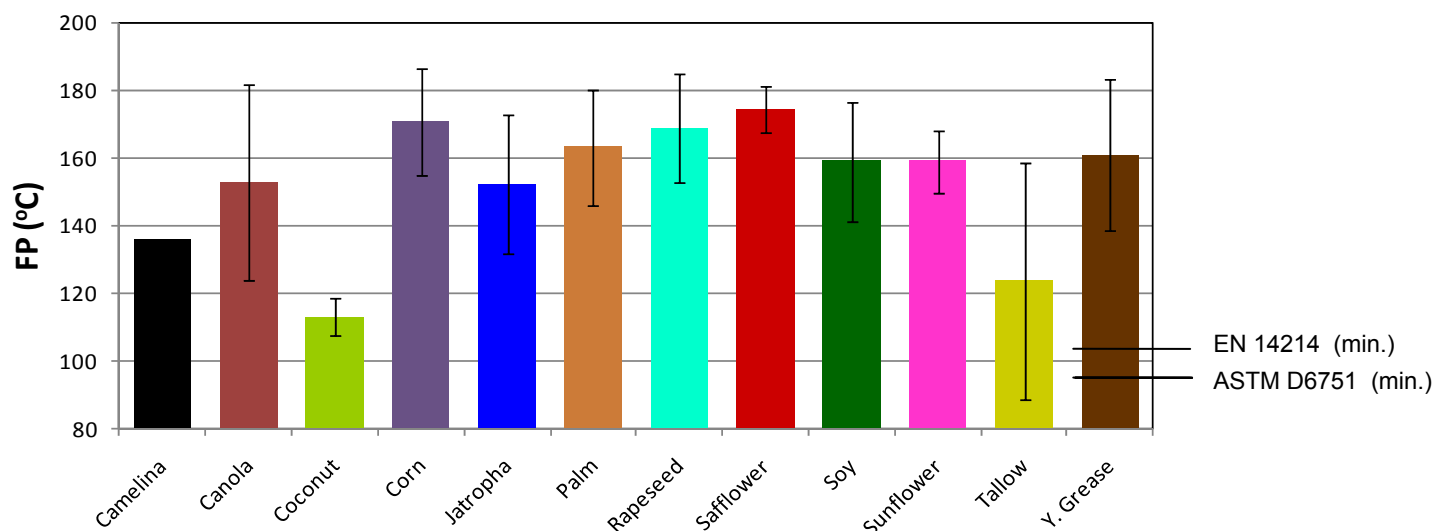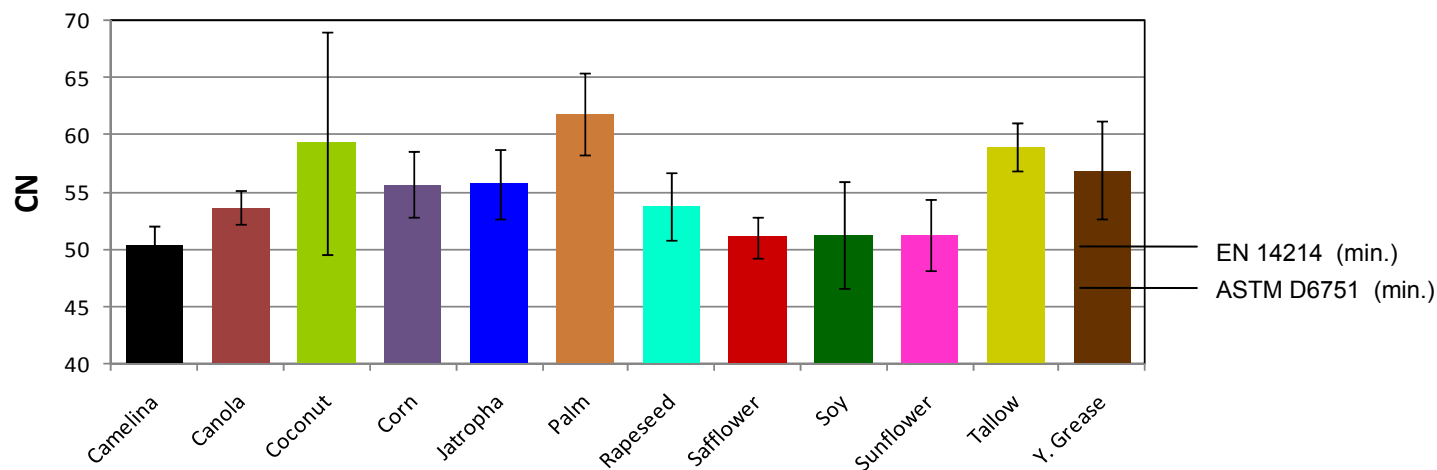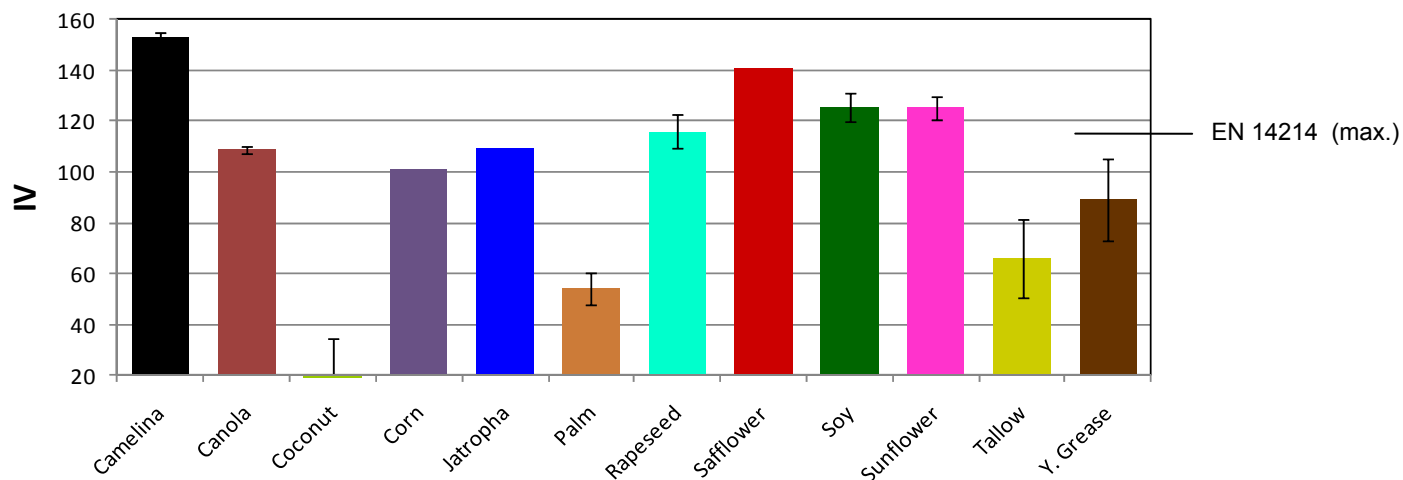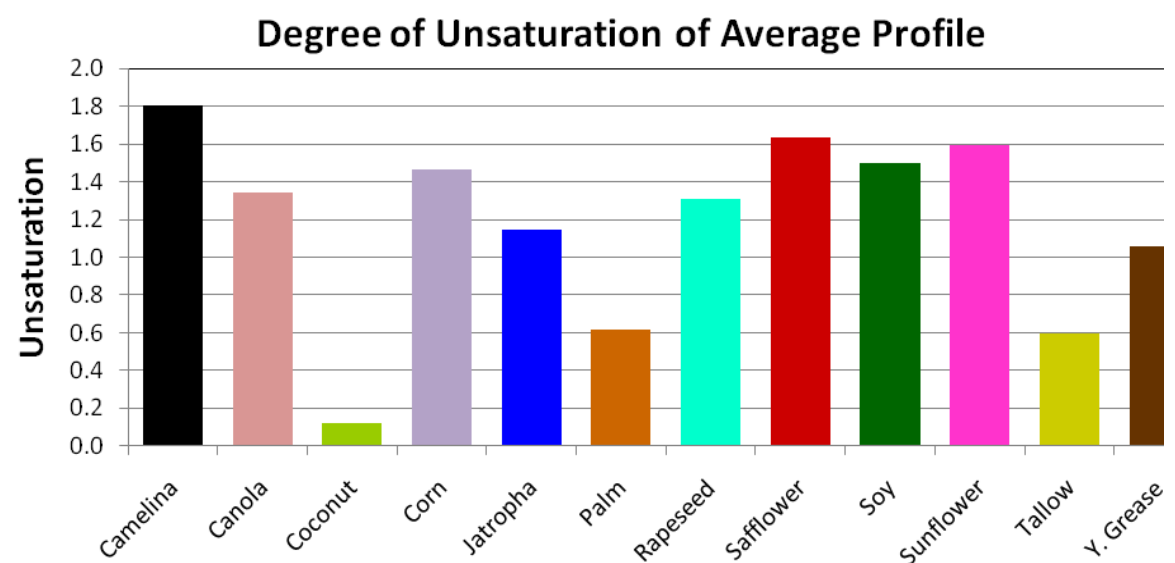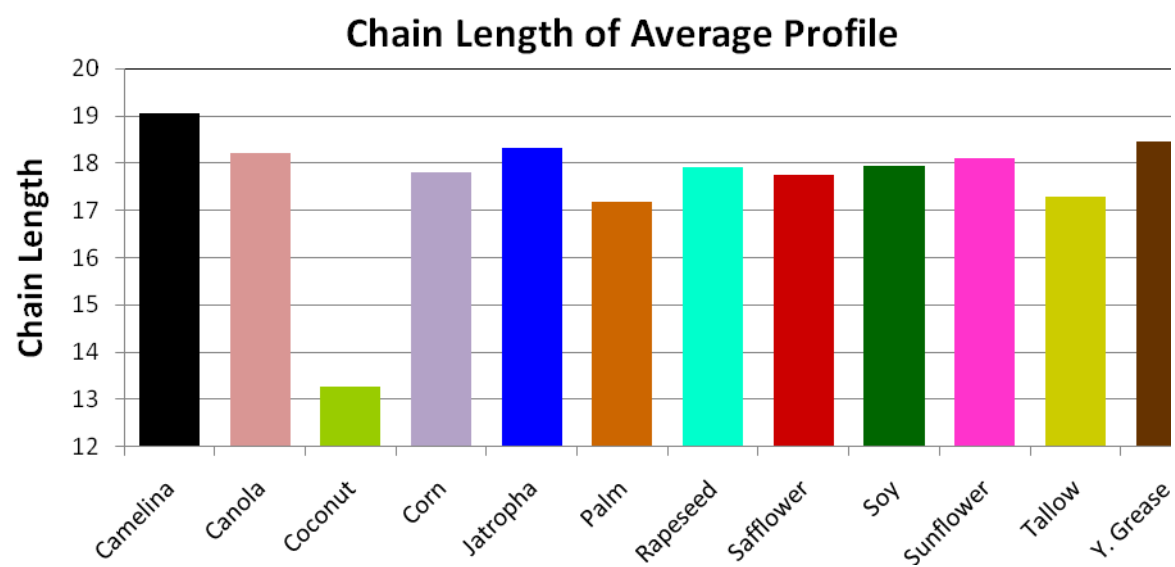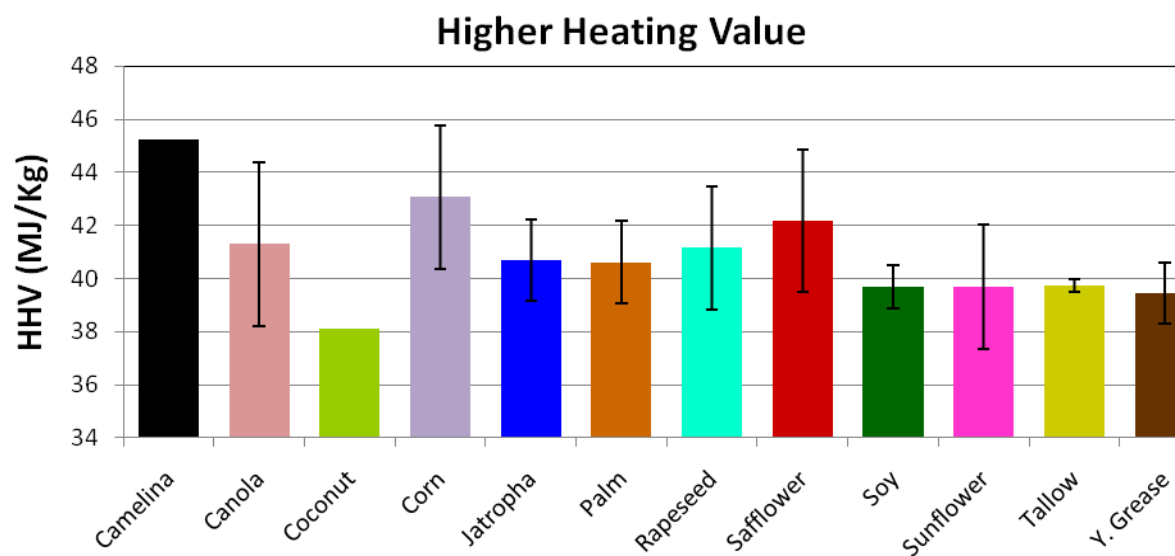
(d)

3.1.5   Cetane Number

Cetane number values for all 12 biodiesel types are also shown in Figure 6c. All 12 easily surpass the ASTM minimum specification of 47, with the highest cetane values being observed for palm-, coconut-, and tallow-derived FAME. The European specification is more stringent, requiring a minimum cetane number of 51. On this basis, biodiesel produced from camelina, safflower, soy, and sunflower are all borderline, and specific batches may have difficulty in meeting the specification. Cetane index values are not shown in Figure 6, as they are not considered reliable.

3.1.6   Iodine Value

ASTM D6751 does not include a specification for iodine value (IV), while EN 14214 has a maximum IV specification of 120 mg I_2/100g FAME. As shown in Figure 6c, rapeseed biodiesel is just below this value of 120, while biodiesel from soy and sunflower are just over the limit. Biodiesel from camelina and safflower have even higher IV levels, and would clearly be "off-spec" with respect to EN 14214, while all other biodiesel types shown here are well below the 120 IV level. Coconut-derived biodiesel has an IV of less than 20 (average of 18.5), hence it does not appear on Figure 6c.

3.1.7   Heating Value

Neither the U.S. nor European biodiesel standards include a specification for heating value. Due to its substantial oxygen content, it is generally accepted that biodiesel of all types has about 10% lower mass energy content (MJ/kg) than petroleum diesel (see Table VI). Figure 6d shows the range of literature-reported energy contents across the 12 biodiesel types investigated. [Only higher heating values (HHV) are shown here, but a graph of lower heating values (LHV) shows similar patterns.] Some minor differences among the biodiesel types are seen, with camelina having the highest HHV at 45.2 MJ/kg (based upon a single report), followed by corn and safflower at 43.1 and 42.2 MJ/kg, respectively. FAME produced from soy, sunflower, tallow, and yellow grease are all just below 40 MJ/kg, while FAME from coconut is much lower at 38.1 MJ/kg. It should be emphasized that with several biodiesel types, the data reported for heating values is very sparse. In addition, confusion between LHV and HHV is likely in several literature reports.

3.1.8   Other Properties

The calculated properties of average chain length and average degree of unsaturation are also shown in Figure 6d. Eleven of the 12 biodiesel fuels have average chain lengths varying from 17 to 19, with camelina-derived fuel being the longest at 19.1. Coconut-derived biodiesel has a considerably shorter average chain length of 13.4. The average degree of unsaturation varied substantially across the range of 12 biodiesel types – from a low of 0.12 (for coconut) to a high of 1.81 (for camelina). As discussed below, this variability in unsaturation is one of the most important factors in explaining many other differences in properties and performance among the range of biodiesel types.

3.2   Properties of Biodiesel from Algal Lipids

Despite the current emphasis on use of algal lipids as biodiesel feedstocks, there are very few literature reports of actual biodiesel samples produced from algae, and even fewer reports of relevant fuel properties from such algal-derived materials. Miao et al. reported the production of biodiesel from *Chlorella protothecoides*, and showed that it satisfies several of the ASTM specifications for biodiesel. [52,53] Also, Francisco et al. produced biodiesel samples from six different algal species, and showed that they meet several of the specifications for European biodiesel – including iodine value (IV). [54]

Considering the high degree of unsaturation of many algal FA profiles (see Table IV and Figure 4) it is surprising that these biodiesels would meet the European IV specification. It is also expected that such highly unsaturated materials would have difficulty in meeting the oxidation stability requirements within either the U.S. or European biodiesel standards. Assessing the suitability of algal-derived FAME as a biodiesel fuel is clearly an area requiring further study.

3.3 Relationships between Composition and Properties

The physical and chemical properties of biodiesel are largely dictated by the specific compositional profile of the FAME material. Several researchers have investigated relationships between particular properties and compositional features by careful study of pure compounds, or mixtures of pure compounds. [55,56] In this study, the authors have compiled considerable information on properties and compositions of complete FAME products from many feedstocks, enabling investigation of relationships across a range of realistic biodiesel types.

As a first step, a simple correlation matrix utilizing the average physical/chemical properties of the 12 biodiesel types shown in Table VIII was developed. Separate matrices were developed with and without including coconut-derived FAME. Both correlation matrices are shown in Table IX. Highlighting (by different shading colors) is used to indicate correlation values exceeding 0.70, 0.80, and 0.90. This clearly demonstrates the important relationships between certain properties, and highlights the significance of the computed property, average unsaturation, which is highly correlated with several other properties.

The two compositional features of FAME generally regarded as most important in determining fuel properties are FA chain length and degree of unsaturation. To explore these relationships more thoroughly using the robust set of FAME data, a set of graphical displays was generated in which the average of 11 fuel properties for the 12 biodiesel types are plotted against average chain length, and against average degree of unsaturation. These graphs are shown in Figure 7. Least-squares regression fits are included on each of the "degree of unsaturation" graphs. The results and implications from each case are discussed below.

3.3.1 Kinematic Viscosity

Viscosity is a measure of resistance to flow of a liquid due to internal friction of one part of a fluid moving over another. [57] This is a critical property because it affects the behavior of fuel injection. In general, higher viscosity leads to poorer fuel atomization. [58] High viscosity can cause larger droplet sizes, poorer vaporization, narrower injection spray angle, and greater in-cylinder penetration of the fuel spray. [59,60,61,62,63] This can lead to overall poorer combustion, higher emissions, and increased oil dilution. The viscosity of biodiesel is typically higher than that of petroleum diesel – often by a factor of two. The viscosity of biodiesel blends increases as the blend level (B-level) increases. (The viscosity of straight vegetable oil is much higher yet, and is the main reason why such oils are unacceptable as diesel blendstocks.)

It has been shown that in a light-duty, common rail injection system, higher viscosity FAME resulted in increased delay in start of injection, reduced injection volume, and increased injection variability. [64,64] As shown in Figure 5, viscosity is greatly affected by temperature. [65] Hence, many of the problems resulting from high viscosity are most noticeable under low ambient temperature and cold-start engine conditions. 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.[66] This, in turn, could lead to engine performance and emissions problems.

Viscosity of individual FAME molecules is known to increase with FA carbon number. [57,67,65]. However, as shown in Figure 7a, the average carbon number of most common biodiesel types does not vary over a wide range. The impacts of increased carbon number within the alcohol used to produce FAME is smaller and less certain. Several researchers have reported slight increases in viscosity upon changing the alcohol from methanol, to ethanol, to propanol. [65,68,57,69,70]

A high degree of correlation between biodiesel density and viscosity has been noted in the literature, with higher density leading to lower viscosity. [71] However, the correlation between density and specific gravity from the data set (shown in Table IX) is not very high, with a value of -0.62 (excluding coconut-derived FAME). Viscosity correlates more strongly with the degree of unsaturation, with higher unsaturation leading to lower viscosity (although coconut-derived FAME is an exception). Furthermore, the double bond configuration influences viscosity, with *trans* configuration giving higher viscosity than *cis*. [67,57] Most natural oils are dominated by *cis* double bonds, but some yellow grease (waste cooking oils) can have substantial levels of the *trans* configuration. [67] The location of the double bond within the FA chain apparently has little influence on viscosity.

3.3.2 Density

Fuel density is a key property that affects engine performance. Because fuel injection pumps meter fuel by volume, not by mass, a greater or lesser mass of fuel is injected depending upon its density. Thus, the air-fuel ratio and energy content within the combustion chamber are influenced by fuel density.

In general, densities of biodiesel fuels are slightly higher than those of petroleum diesel, and increasing the B-level of biodiesel blends will increase the blend's density. As shown in Figure 7a, FAME density is strongly affected by the degree of unsaturation, with higher unsaturation leading to increased density. [67] (Note: in this study, density and specific gravity are used interchangeably. Specific gravity is most frequently reported in the literature, although density is the specification metric.) Table IX shows the correlation coefficient between specific gravity and average unsaturation to be 0.75 (including coconut).

It has been reported that biodiesel density is also affected by chain length, with higher chain length leading to lower fuel density. [67] However, this does not appear to be the case for the set of 12 biodiesel fuels investigated here, as indicated by the data plotted in Figure 7a or by the correlation coefficients shown in Table IX. No information was found regarding the effect of alcohol length or branching upon density.

3.3.3 Cold Flow Properties

Low temperature operability is one of the most important considerations for users of biodiesel. Just as with conventional diesel fuel, precautions must be taken to ensure satisfactory low temperature operability of biodiesel and its blends.[45] 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. There is no single best way to assess low temperature operability, and the existing fuel standards (both U.S. and European) do not include explicit specifications for cold flow properties – either for conventional diesel or biodiesel (or blends of the two). However, the fuel provider is generally required to give an indication of the cold flow properties by reporting the cloud point (CP) of the fuel. A number of other laboratory tests are commonly used to define low temperature properties of biodiesel (and conventional diesel). These are listed below in Table X.

Table IX. Correlations among Biodiesel Fuel Properties

Correlation Matrix Including Coconut

Properties	Sulfur	Vis.	CP	PP	CFPP	Flash Point	Cetane No.	Cetane Index	Iodine Value	Specific Gravity	LHV	HHV	Avg. Chain Length	Avg. Unsat.
Sulfur	1.00													
Viscosity	0.41	1.00												
Cloud Point	0.44	0.50	1.00											
Pour Point	0.44	0.54	0.94	1.00										
CFPP	0.47	0.32	0.95	0.92	1.00									
Flash Point	-0.25	0.54	-0.22	-0.05	-0.34	1.00								
Cetane No.	0.40	0.01	0.60	0.67	0.61	-0.39	1.00							
Cetane Index	0.14	-0.51	-0.40	-0.29	-0.27	-0.28	-0.18	1.00						
Iodine Value	-0.28	0.30	-0.37	-0.43	-0.45	0.55	-0.92	0.15	1.00					
Specific Gravity	-0.16	0.15	-0.45	-0.42	-0.51	0.27	-0.68	0.58	0.69	1.00				
Lower Heating Value	0.19	0.42	-0.11	0.04	-0.23	0.35	-0.03	0.52	0.31	0.64	1.00			
Higher Heating Value	-0.29	0.04	-0.22	-0.25	-0.28	0.27	-0.52	0.63	0.69	0.58	0.77	1.00		
Avg. Chain Length	0.01	0.73	0.12	0.08	-0.07	0.57	-0.54	-0.12	0.81	0.61	0.53	0.61	1.00	
Avg. Unsaturation	-0.35	0.27	-0.43	-0.43	-0.50	0.63	-0.90	0.20	0.98	0.75	0.39	0.73	0.79	1.00

Correlation Matrix Excluding Coconut

Properties	Sulfur	Vis.	CP	PP	CFPP	Flash Point	Cetane No.	Cetane Index	Iodine Value	Specific Gravity	LHV	HHV	Avg. Chain Length	Avg. Unsat.
Sulfur	1.00													
Viscosity	0.60	1.00												
Cloud Point	0.43	0.57	1.00											
Pour Point	0.42	0.59	0.93	1.00										
CFPP	0.46	0.48	0.96	0.93	1.00									
Flash Point	-0.45	-0.04	-0.51	-0.32	-0.52	1.00								
Cetane No.	0.49	0.69	0.77	0.87	0.69	-0.22	1.00							
Cetane Index	0.14	-0.51	-0.40	-0.29	-0.27	-0.28	-0.18	1.00						
Iodine Value	-0.50	-0.72	-0.75	-0.87	-0.70	0.21	-0.97	0.15	1.00					
Specific Gravity	-0.26	-0.62	-0.69	-0.68	-0.67	-0.08	-0.61	0.58	0.54	1.00				
Lower Heating Value	0.12	-0.29	-0.34	-0.19	-0.35	-0.05	0.20	0.52	-0.15	0.51	1.00			
Higher Heating Value	-0.41	-0.84	-0.41	-0.47	-0.38	-0.06	-0.42	0.63	0.56	0.44	0.66	1.00		
Avg. Chain Length	-0.32	-0.39	-0.34	-0.56	-0.44	-0.13	-0.59	-0.12	0.67	0.48	0.05	0.49	1.00	
Avg. Unsaturation	-0.59	-0.79	-0.82	-0.87	-0.76	0.35	-0.94	0.20	0.96	0.65	0.03	0.62	0.65	1.00

Kinematic Viscosity
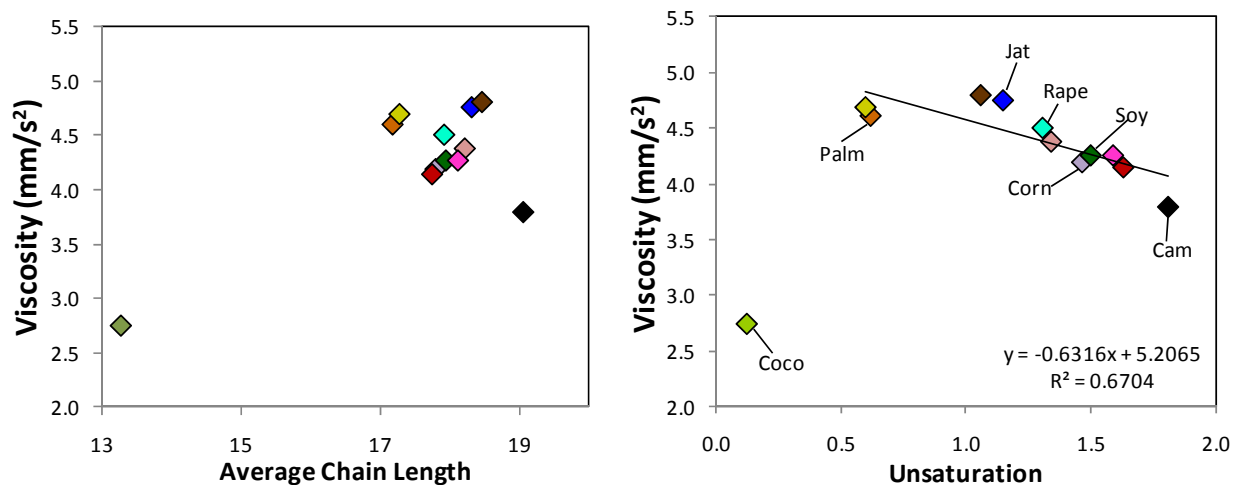
Specific Gravity
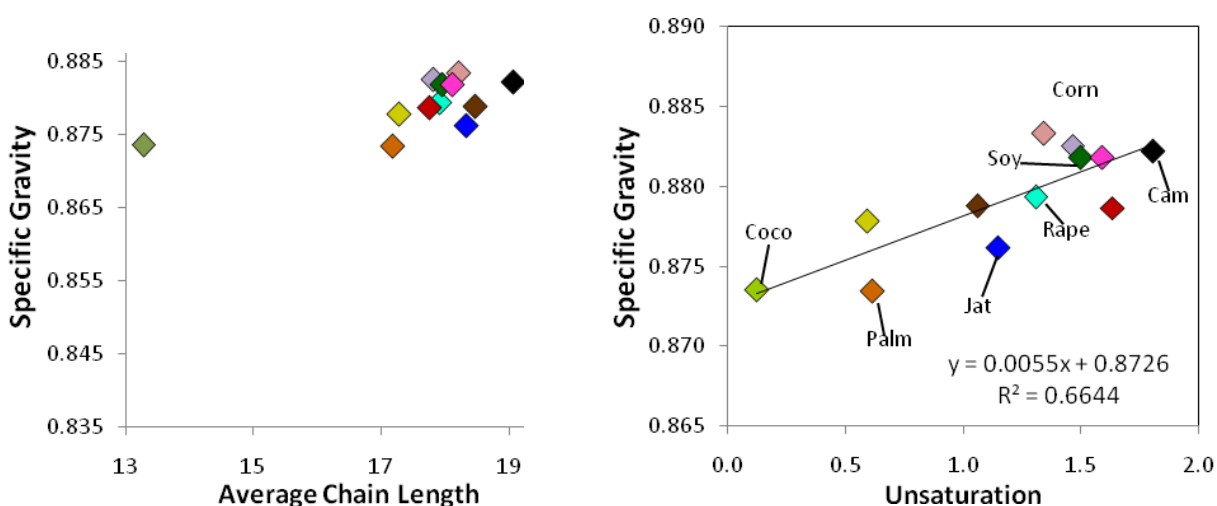
(a)

Figure 7,a,b,c,d. Relationships between Biodiesel Unsaturation/Chain Length and Other Fuel Properties

- Average Chain length computed from compositional profiles in Table III
- Average degree of unsaturation computed from compositional profiles in Table III
- Least squares linear regression fits computed with and without coconut FAME
- Biodiesel feedstock abbreviations: "Coco" = coconut; "Jat" = Jatropha; "Cam" = camelina

Cloud Point
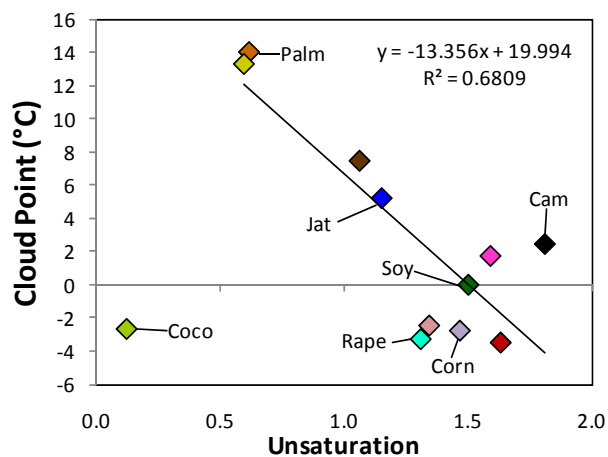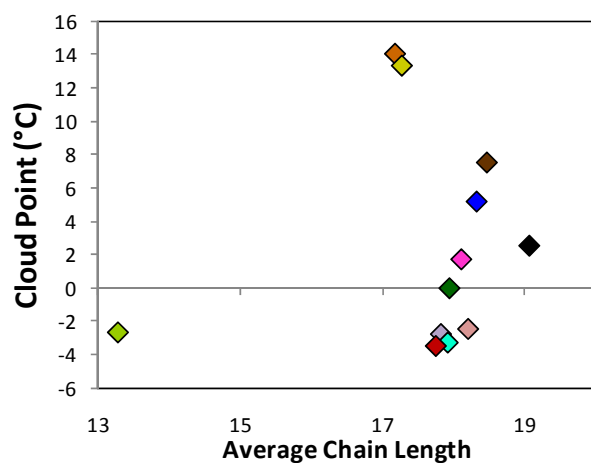
Pour Point
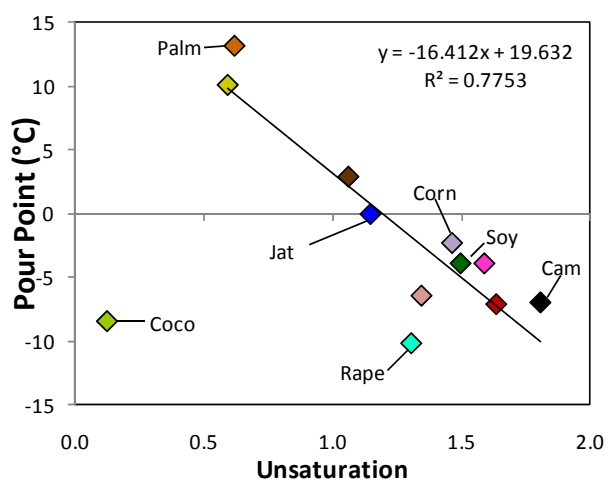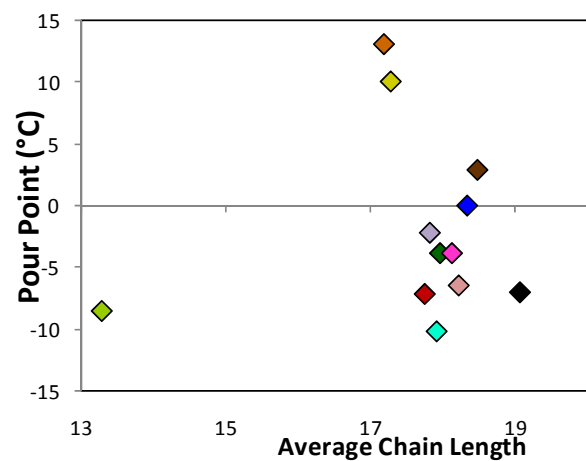
Cold Filter Plugging Point (CFPP)
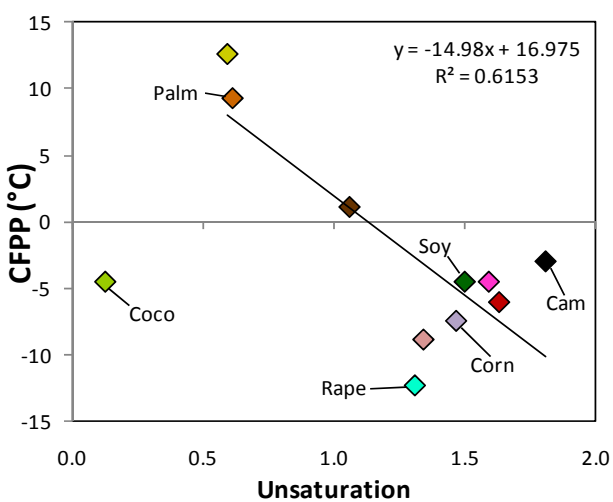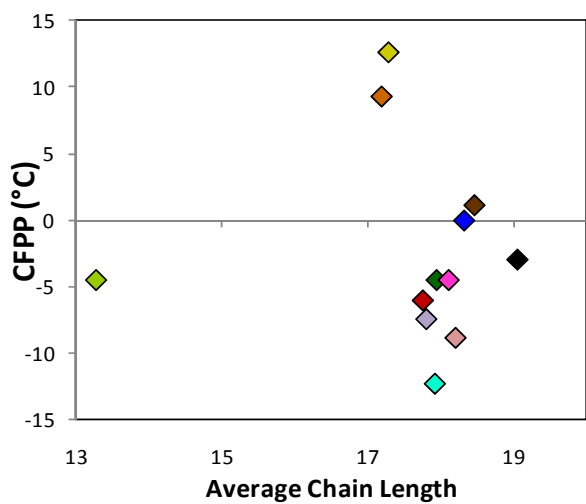
(b)

Cetane Number
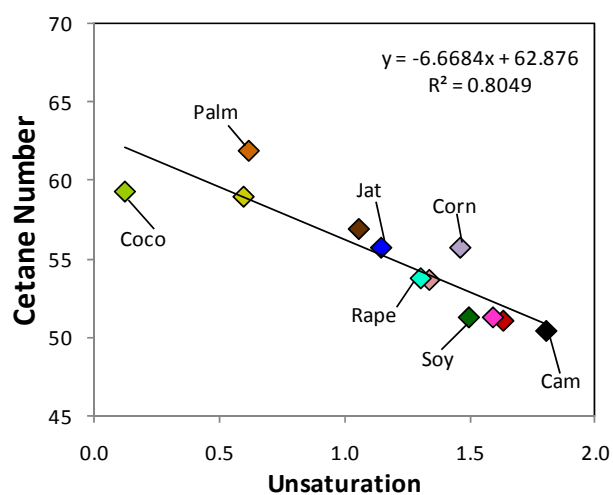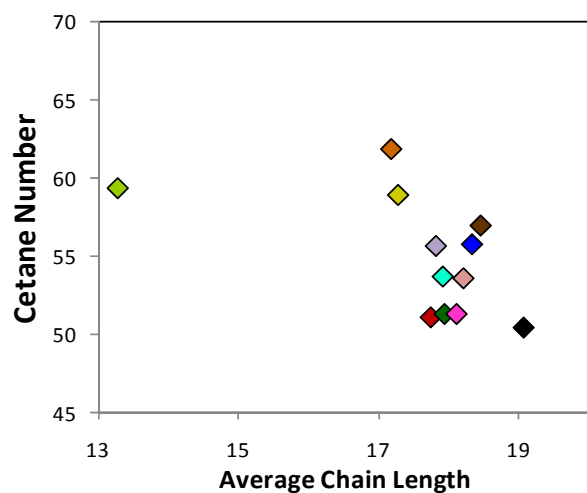
Cetane Index
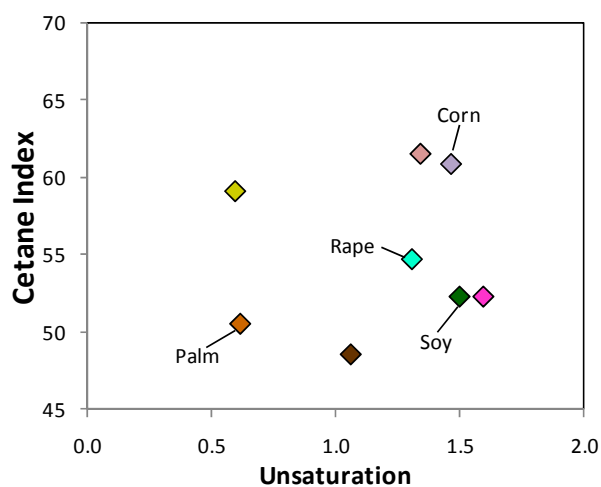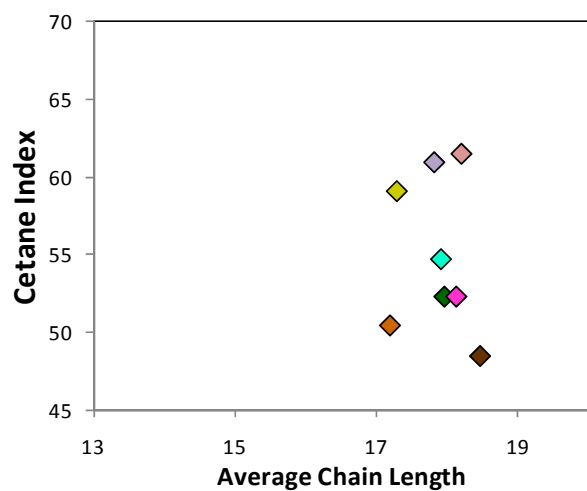
Iodine Value
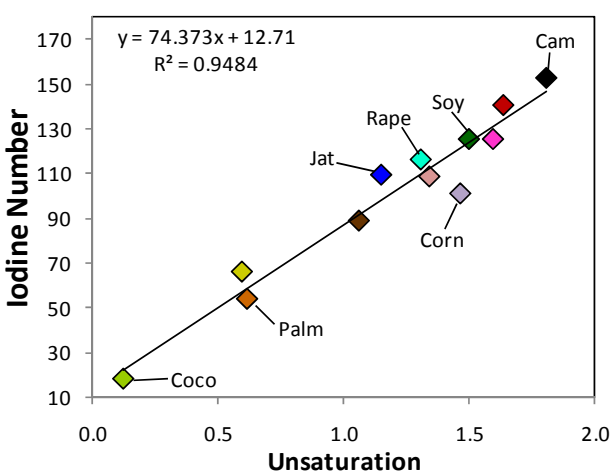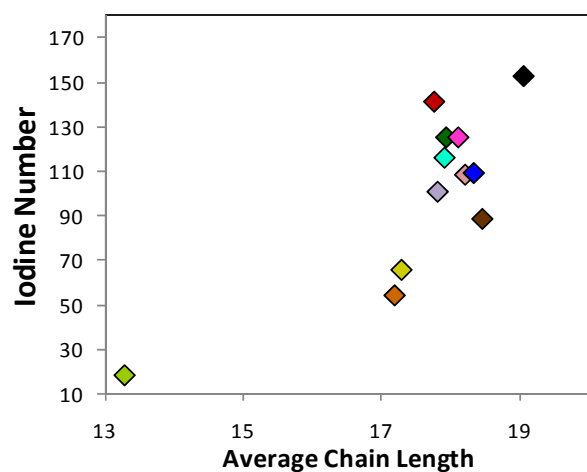
(c)

Flash Point
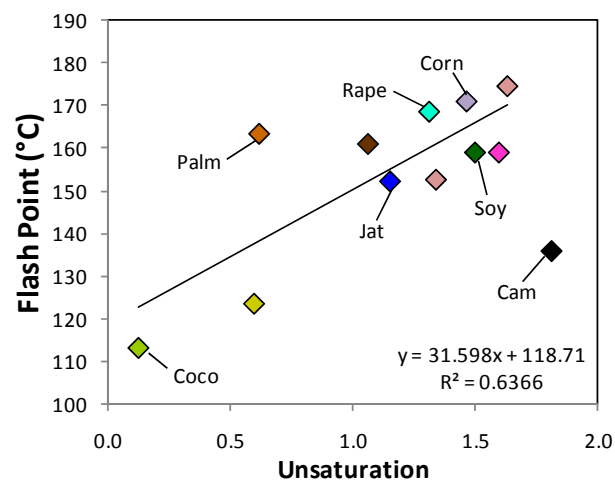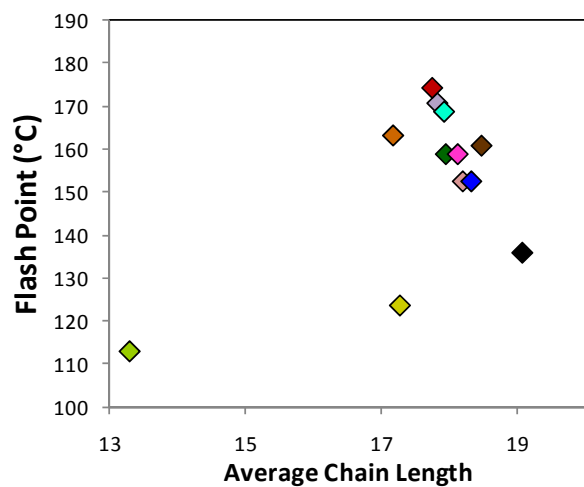
Lower Heating Value (LHV)
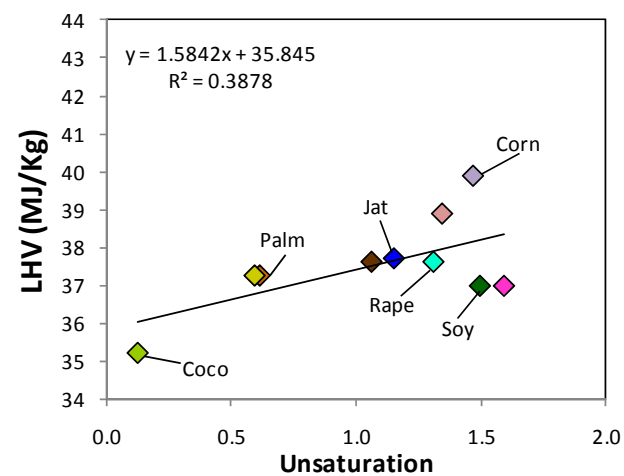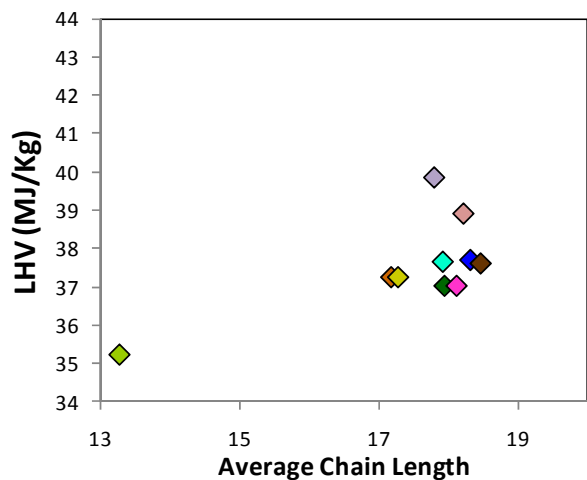
Higher Heating Value (HHV)
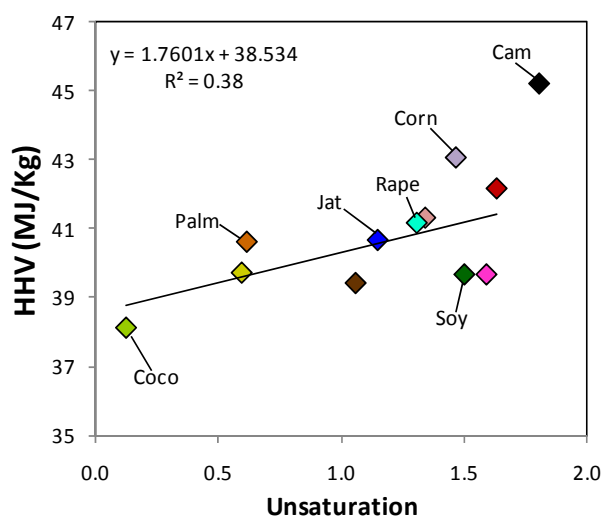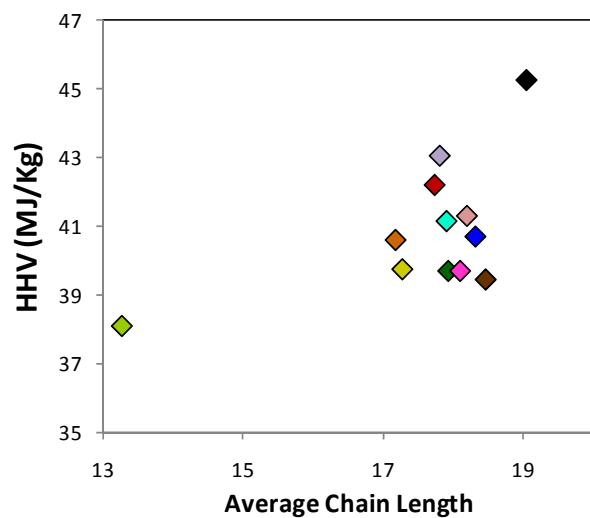
(d)

Table X. Low Temperature Performance Tests for Biodiesel

Test Name	Abbreviation	Test Method(s)
Cloud Point	CP	EN 23015, ASTM D2500, ASTM D5773
Pour Point	PP	ASTM D97, ASTM D5949
Cold Filter Plugging Point	CFPP	EN 116, IP 309, ASTM D6371
Low Temp Filterability Test	LTFT	ASTM D4539
Wax Appearance Point	WAP	ASTM D3117
Cold Soak Filterability	-	ASTM D7501

A good review of low temperature properties and performance of biodiesel is available in the literature.[72] In addition, a recent NREL publication provides useful guidance for addressing low temperature operability issues, as well as other in-use handling issues.[45] Poor cold flow properties result from the presence of long-chain, saturated fatty acid esters present in biodiesel. Saturated methyl esters longer than C_{12} significantly increase CP and PP, even when blended with conventional diesel. [73,74] In general, the longer the carbon chain, the higher the melting point, and poorer the low temperature performance. [75,70,67,76]

Feedstocks with highly saturated fatty acid structures (such as palm oil and tallow) produce biodiesel fuels with poor cold flow properties; whereas feedstocks with highly unsaturated fatty acid structures (such as rapeseed and safflower oil) produce fuels having better performance. Although the relationship between carbon chain length and low temperature properties is quite strong for pure FAME compounds, the effect appears more subtle when considering complex mixtures of FAME in actual biodiesel samples. For example, the three low temperature properties included in Figure 7b do not show a clear relationship with average chain length. The graphs in this figure show very similar patterns for all three low temperature properties: CP, PP, and CFPP. In addition, the values in Table IX indicate extremely high correlation among these three properties, suggesting that any one could be used as an indicator of the others.

In large part, the reason the analysis does not indicate a stronger relationship between chain length and low temperature properties is because the definition of average chain length does not distinguish between saturated and unsaturated FA chains. Degree of unsaturation has a strong effect on low temperature properties, with higher unsaturation leading to greatly improved low temperature performance. Thus, the effect of unsaturation masks the effect of chain length on low temperature properties. More sophisticated data analysis techniques would be required to properly determine the separate effects of multiple variables upon fuel property relationships.

Figure 7b indicates that very similar relationships between unsaturation and low temperature properties are seen regardless of which metric is used. (The regression lines and equations shown for all three are derived from a data set excluding coconut-derived FAME.) Of these three properties, only CP can be defined thermodynamically, as it is governed by solid-liquid equilibrium as a function of temperature. (True equilibrium conditions may not actually 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 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.[77,78,79] In general, these models show good agreement with laboratory measurements.

Wax crystallization is initiated by "close packing" of molecules. Thus, factors that disrupt or inhibit close packing of highly ordered molecules will decrease CP (and improve the other low temperature properties as well). Such structural disorder is increased with branching in either the FA chain or the alcohol portion

of FAME. [80,69] Replacing methanol with ethanol to produce FAEE results in slightly improved low temperature performance, as ethyl esters typically have melting points 5-10°C lower than the comparable methyl esters. [79,81,82,83,84] Introduction of a double bond also disrupts the close packing of molecules. [67,76] Furthermore, differences in double bond orientation have been noted, with the *cis* configuration providing better low temperature test performance than *trans*. [85]

Increasing B-level of biodiesel typically leads to worsening of low temperature performance. However, blending of different components often results in non-linear effects with respect to low temperature properties.[86] For example, it has been reported that the very poor low temperature performance of palm-based biodiesel can be improved by blending with jatropha-based fuel. [87,88]

In recent years, another low temperature operability problem has been recognized, resulting from the formation of insoluble particles upon storage at cool temperatures – though generally above the cloud point. These insolubles arise from precipitation of trace-level non-FAME impurities, not from the major FAME components themselves. Because of these operability problems, ASTM has adopted a new Cold Soak Filterability test within the biodiesel standard, D6751. The two major families of impurities identified as causing such precipitate problems are saturated mono-glycerides and sterol glucosides. [89,90,91,92,93,46] Figure 8 shows representative structures of these compounds.
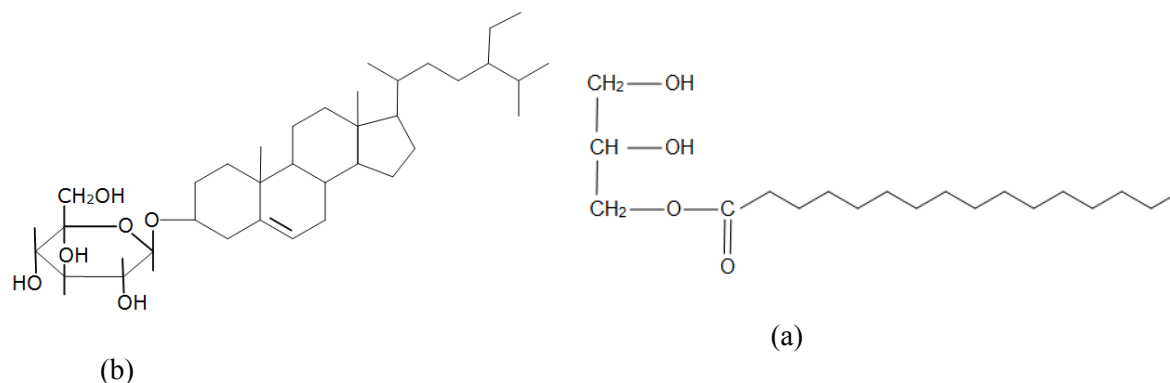
Figure 8a,b. Typical Structures of Compounds Responsible for Poor Cold Soak Filtration
a) sterol glucosides; b) saturated mono-glycerides

3.3.4 Cetane Number

Cetane Number (CN) is a measure of a fuel's autoignition quality characteristics. Since biodiesel is largely composed of long-chain hydrocarbon groups (with virtually no branching or aromatic structures) it typically has a higher CN than ULSD, and increasing the B-level of biodiesel blends increases the CN of the blend. [94,95] There are exceptions, however, when a relatively low CN biodiesel is blended with a relatively high CN ULSD. In such cases, increasing B-level results in decreasing CN of the blend. Biodiesel produced from feedstocks rich in saturated fatty acids (such as tallow and palm) have higher CN than fuels produced from less saturated feedstocks (such as soy and rapeseed). The effect upon CN of branching in the alcohol used to produce the biodiesel is very small, and difficult to discern. [80,96] The CN of pure FAME molecules increases with chain length. However, as was the case with the low temperature properties discussed above, the effect of chain length is masked when considering complex mixtures of FAME fuels. Figure 7c shows very little relationship between CN and average chain length; this is also reflected in the low correlation coefficients in Table IX.

On the other hand, degree of unsaturation is strongly correlated with CN (correlation coefficient > 0.9), with increasing degree of unsaturation leading to decreasing CN. [95,80,67] Lapuerta et al. have recently

proposed a predictive equation for FAME CN that is largely driven by the number of double bonds in the FAME (as well as the FAME's carbon number). [97] In the same paper, the authors note the high correlation between CN and iodine value (IV). This is also apparent from the high correlation coefficients for CN and IV shown in Table IX.

No correlation between CN and cetane index (CI) is apparent from the data. (This is seen by the very low correlation coefficients in Table IX.) In addition, CI has no meaningful correlation with average unsaturation or IV. These observations suggest that CI values reported in the literature are not reliable, and highlight the problem that at present, a valid method for computing CI for biodiesel does not exist.

3.3.5   Iodine Value

Iodine Value (IV) is determined by measuring the amount of I_2 that reacts by addition to carbon-carbon double bonds; thus, IV is directly related to FAME unsaturation. This is clearly seen in Figure 7c, and by the high correlation coefficients in Table IX.

IV was originally included as a specification in the European biodiesel standard, EN 14214, to ensure satisfactory oxidative stability of the fuel. However, IV is simply a measure of total unsaturation, while oxidative stability is more strongly influenced by the amount of FAME molecules having multiple double bonds (see discussion below in Section 3.3.9). For this reason, there is some controversy about the need for an IV standard at all, and certainly about the rather restrictive maximum IV value of 120g I_2/100g biodiesel set by EN 14214.

The Worldwide Fuel Charter -- established by a collection of U.S., European, and Japanese automobile manufacturers associations -- also recommends an IV specification, but with a less restrictive allowable maximum of 130g I_2/100g biodiesel. [98] As can be seen from Figure 6c, soy-derived biodiesel is much more likely to satisfy this higher IV specification.

The ASTM biodiesel standard does not include an IV specification, believing that oxidative stability is better addressed by different test methods; namely, the Rancimat oxidative stability test (Method EN 14112). Others have argued that there is no need for an IV specification because the cetane number specification effectively limits unsaturation, since CN and IV are highly correlated. [97]

3.3.6   Flash Point

Flash point is inversely related to fuel volatility. The biofuel specifications for flash point are meant to guard against contamination by highly volatile impurities – principally excess methanol remaining after product stripping processes. Of the 12 biodiesel materials investigated in this study, it is expected that coconut-derived FAME would have the lowest inherent flash point, since its composition includes much more light material ($\leq C_{12}$) than the other 11 FAMEs (see compositional profiles in Figure 2).

Overall, the dataset does not indicate a high degree of correlation between flash point and any other property. The highest correlation factor in Table IX is 0.63, between flash point and average unsaturation (including coconut).

3.3.7   Heating Value

Due to its high oxygen content, biodiesel has lower mass energy values than petroleum diesel. Therefore, increasing the B-level of biodiesel blends results in decreasing energy content. (The same relationships exist whether HHV or LHV is being considered.) As the FA carbon chain increases (for a constant unsaturation level) the mass fraction of oxygen decreases, so the heating value increases. [99,100]

However, the increase in heating value with chain length is not readily apparent in the graphs of Figure 7d or the correlation matrices of Table IX.

Unsaturation level has a somewhat stronger influence upon heating values. Compared to saturated esters, unsaturated esters have lower mass energy content (MJ/kg), but higher volumetric energy content (MJ/gal.) [67] This can be confusing, since mass energy content is typically measured in the laboratory, while fuel is metered and sold on a volumetric basis. The heating values plotted in Figure 7d are on a mass basis (MJ/kg), and therefore might be expected to show a decrease with increasing unsaturation. In fact, no significant relationship is observed. Another point to remember is the confusing and inconsistent reporting of heating values in the literature. Further evidence of these problems is the rather low degree of correlation between LHV and HHV seen in the correlation matrices of Table IX.

Other relationships between heating values and physical properties of FAME have been reported. In particular, mass energy content has been shown to decrease with Iodine Value [99] (which is itself highly correlated with degree of unsaturation), and to increase with viscosity, [100] but to decrease with density.

3.3.8 Lubricity

Lubricity refers to the reduction of friction between solid surfaces in relative motion. [44] Two general mechanisms contribute to 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. In many cases, the fuel itself is the only lubricant within a fuel injector. With the increasing operational demands of modern injection systems – due to higher pressures, injection rate shaping, multiple injections per cycle, and other features – maintaining adequate lubricity is more critical than ever. However, as the need for improved lubricity has increased, the natural lubricity of petroleum diesel fuels has decreased. The high degree of hydrotreatment necessary to produce ULSD effectively removes all hetero-atom containing molecules (O, N, and S) which have improved lubricity compared to hydrocarbons. In general, lubricity effectiveness decreases in the order of O>N>S>C.[101]

Biodiesel from all feedstocks is generally regarded as having excellent lubricity, and the lubricity of ULSD can be improved by blending with biodiesel. Because of its naturally high lubricity, there is no lubricity specification for B-100 within either the U.S. or European biodiesel standards. However, the U.S. standard for B6-B20 blends (ASTM D7467) does include a lubricity specification, as does the conventional diesel fuel standard, ASTM D975. Low B-levels (often just 1-2%) typically provide satisfactory lubricity to ULSD. [101,45]

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.[101,102] It has been noted that purification of biodiesel by means of distillation reduces its lubricity because these impurities are removed. The effect of unsaturation upon lubricity is unclear, with some researchers reporting positive effects of carbon-carbon double bonds[101] while others report no effect.[103]

The positive impact of biodiesel impurities upon lubricity is particularly noteworthy, as some of the same impurities (such as monoglycerides) are responsible for poor low temperature operability problems. Efforts to reduce these impurities (to improve low temperature properties) could have the unintended consequence of worsening lubricity.

3.3.9   Oxidative Stability

Oxidative stability is arguably the most important property with respect to in-use performance of biodiesel. 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.[104,105] Despite this importance, oxidative stability is not included in the tabular or graphical summaries of FAME properties (Table VIII and Figure 6, respectively). The reason for this omission is that oxidative stability is determined not only by FAME compositional properties, but is also highly dependent upon the age of the biodiesel and the conditions under which it has been stored. Furthermore, many biodiesel samples contain additives that improve stability without affecting the gross composition.

Oxidative stability is related to unsaturation. In general, higher unsaturation leads to poorer stability, although the autoxidation of unsaturated fatty compounds proceeds at different rates depending upon the number and position of the double bonds. [104] Oxidative degradation processes are initiated by extraction of a hydrogen atom from a carbon adjacent to a double bond – the so-called allylic position.[106,67] 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, which contains two bis-allylic groups (see Table II). When using purified methyl esters of oleic acid (18:1), linoleic acid (18:2), and linolenic acid (18:3), the relative rates of autoxidation have been measured to be 1:41:98. [107,108]

The importance of polyunsaturated FAME (as opposed to monounsaturated FAME) with respect to fuel stability has been recognized by many researchers. Ramos et al. defined a parameter called degree of unsaturation (DU) similar to the calculated property discussed above, but weighted di- and tri-unsaturated species twice as much as mono-unsaturated species. [109] Park et al. developed a predictive equation for biofuel stability that was based upon the concentrations of just two FAME species: linoleic FAME (18:2) and linolenic FAME (18:3). [110]

The relative amounts of saturated and unsaturated esters comprising biodiesel for 12 common feedstocks are depicted below in Figure 9a. These allocations were based on the average fuel compositional data for each FAME type, shown in Table III. Figure 9a illustrates that the saturate/unsaturate profiles vary widely over this range of 12 biodiesel fuels. At one extreme is coconut-derived FAME, which is approximately 90% saturated and 8% mono-unsaturated. Very high oxidative stability would be expected for coconut-derived FAME, since it contains only about 2% polyunsaturated species.

Biodiesel feedstocks that produce fuels having over 50% polyunsaturated FAME include camelina, corn, safflower, soy, and sunflower; thus, these would be expected to have poor inherent oxidative stability. Camelina-derived biodiesel is particularly noteworthy, as it contains about 35% tri-unsaturated FAME. Consequently, camelina biodiesel may be expected to have especially poor oxidative stability. However, the authors are not aware of any reports of significant stability problems with camelina FAME, although widespread use of this material has not yet occurred.

The algal lipid profiles shown in Figure 9b are strikingly different from the vegetable oil profiles in 9a. For example, five of the twelve algal profiles have over 20% of very highly unsaturated compounds – containing 4 or more double bonds per molecule, while none of the vegetable profiles have measureable quantities of any species with 4 or more double bonds. However, other algal profiles more closely

resemble the vegetable oil profiles, having mainly saturated and mono-unsaturated species, with lesser amounts of di-unsaturated and tri-unsaturated species. The compositional profiles shown in Figure 9b certainly raise questions about the oxidative stability of some algal-derived biodiesel. This is an area requiring further investigation.

(a)

(b)
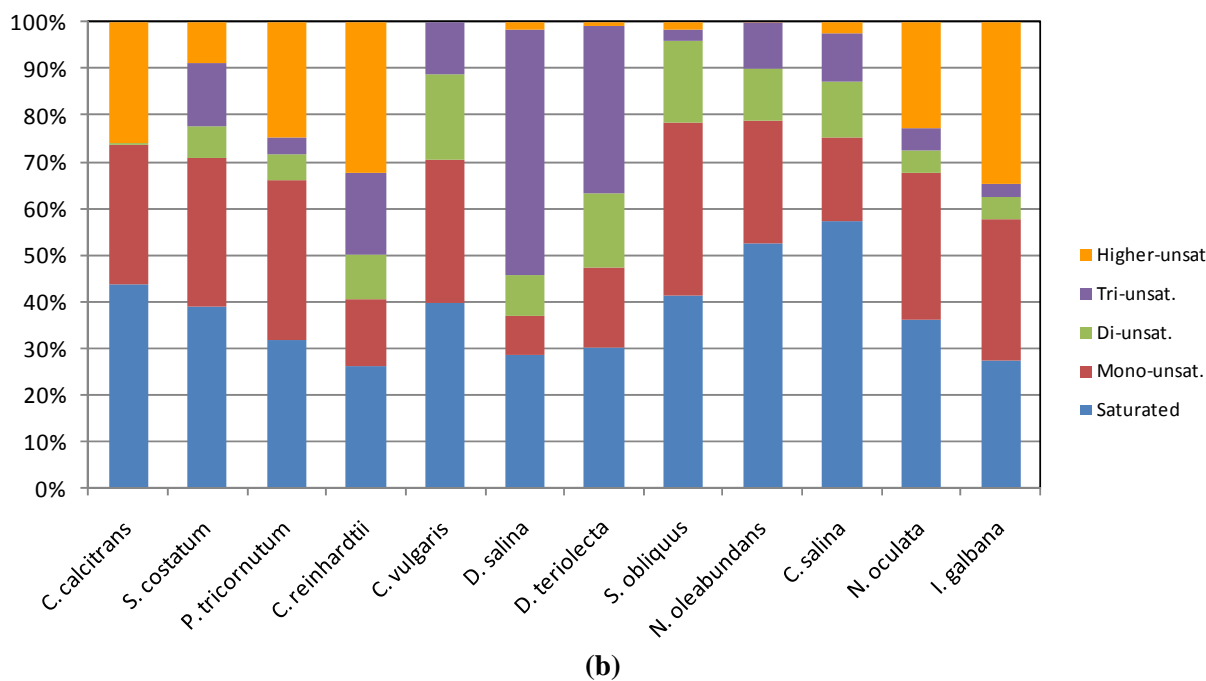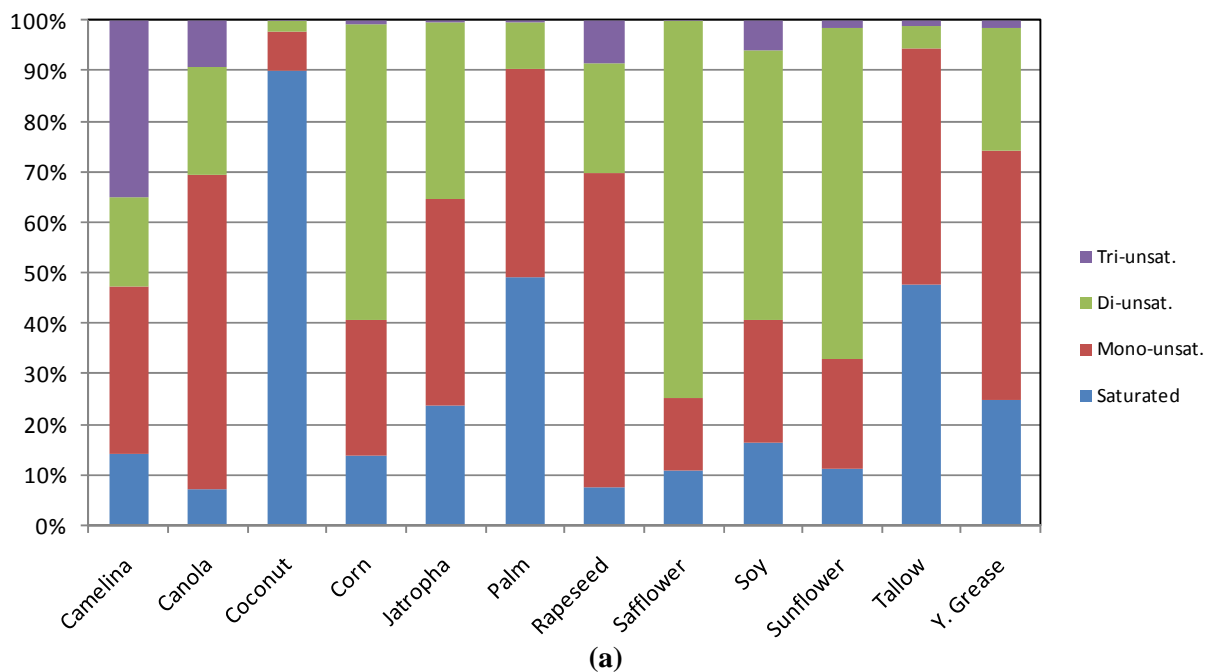
Figure 9a,b. Saturation/Unsaturation Profiles of Biodiesel Feedstocks
a) Animal fat and vegetable oils; b) Algal lipids.

The carbon-carbon double bond orientation is important with respect to oxidative stability. Generally, the *trans* configuration is more stable than *cis*. [108,111] The practical impact of this is limited, however, as all natural fats and oils are dominated by *cis* configuration. Of greater practical value in improving biodiesel stability is the blending of two feedstocks having different levels of inherent oxidative stability. Reported examples of this include blending poor stability jatropha FAME with high stability palm FAME, [87] and blending poor stability soy FAME with high stability palm FAME. [112]

Another reliable method for improving biodiesel stability involves utilization of anti-oxidant additives. [113,114]. Although raw fats and oils usually contain natural anti-oxidants such as tocopherols and caratenoids, synthetic anti-oxidants have generally been found to be more effective. [105,115,116,117,118]

3.4   Optimal Properties for Biodiesel

As seen from the discussion above, changes in compositional features of FAME have significant impacts on the physical/chemical properties of biodiesel. Furthermore, changes in a single compositional feature (such as chain length, chain branching, unsaturation, etc.) generally produces both desirable and undesirable changes in FAME properties. To a certain degree, this is unavoidable, as some properties have antagonistic relationships. For example, compositional features that favor good oxidative stability (high saturation, low unsaturation) lead to poor low temperature operability.

Table XI was constructed to help summarize the significant relationships between FAME composition and FAME properties. This table uses arrows of different thickness and length to characterize the changes in FAME properties resulting from an increase in value of each compositional feature. Long arrows indicate relatively large effects (likely to be noticeable to a perceptive user), while shorter arrows indicate relatively small effects. Thick arrows indicate relationships that seem certain, based upon consistency of literature reports, while narrow arrows are less certain. A "-" symbol indicates that the literature is inconsistent regarding this effect. A blank cell indicates that little (or no) literature information was found pertaining to this effect. It should be emphasized that Table XI represents the best judgment of this report's authors, based upon their literature review and their own analyses of some data, as reflected in the tables and figures of this report.

Due to the conflicting impacts of certain FAME compositional features upon fuel properties, it is not possible to define a specific FA composition that is optimum for all important properties. When considering properties for defining FAME suitability as a fuel blendstock, those that are most important include cetane number, viscosity, cold flow, oxidative stability, and lubricity.[119] Of these five properties, the two that are generally regarded as most critical -- and which vary the most with changes in biodiesel feedstock -- are cold flow and oxidative stability.

Several researchers have investigated design of preferred FAME components to optimize biodiesel's performance with respect to cold flow and oxidative stability. [120,17,109] The general consensus is that an optimum composition would have relatively low levels of saturated FA (to minimize cold flow problems), low levels of di- and tri-unsaturated FA (to minimize oxidative instability), and high levels of mono-unsaturated FA. Some have concluded that palmitoleic acid (16:1) and oleic acid (18:1) provide the best compromise between oxidative stability and cold flow, without excessive reduction of cetane number. [119,120]

Efforts are underway in several laboratories to genetically modify the natural FA composition of vegetable oils (and algal lipids) to improve their suitability as a biodiesel feedstock. [121,122,123] Much of this work is focused on soybeans, with the goal of increasing oleic acid (18:1) and decreasing linoleic acid (18:2) and linolenic acid (18:3). From the standpoint of overall best performance, maximizing

palmitoleic acid (16:1) may be even better, but none of the commonly used vegetable oil feedstocks naturally contain significant amount of this species.

Table XI. Relationships between FAME Level/Composition and Fuel Properties

Arrows indicate change in FAME properties resulting from increases in compositional items*

FAME Composition \ FAME Properties	Viscosity	Density	CP, PP, CFPP	Cetane Number	Iodine Number	Heating Value, MJ/kg	Lubricity	Oxidative Stability
FAME Blend Level (from B0 to B20)	↑	↑	↑	↓↑	↑	↓	↑	↓
Average Chain Length	↑	-	↑	↑		↑		
Chain Branching			↓	↓				
Degree of Unsaturation	↓	↑	↓	↓	↑	↓	-	↓
Alcohol Length and Branching	↑		↓	-				

* Notes:
  Length of arrow indicates relative magnitude of effect
  Thickness of arrow indicates certainty/consistency of effect
  Symbol "-" indicates highly uncertain, or conflicting information
  Blank box indicates that no relevant information was found
  Impact of FAME blend level on Cetane Number depends upon the base fuel's CN

4. EMISSIONS IMPACTS OF BIODIESEL

Based upon extensive engine studies conducted by numerous laboratories – as documented in the previous AVFL-17 Final Report [4] – use of biodiesel and biodiesel blends often provides a significant emissions reduction benefit for three criteria pollutants: HC, CO, and PM. The impacts on NOx emissions are smaller and more difficult to discern. In this section, these criteria emissions impacts are re-investigated, using a database that the authors believe to be more relevant and robust, by excluding some previous studies and adding a few more recent studies. Particular emphasis is placed on B20 blends of biodiesel, as this is the most commonly used blending ratio, and is the maximum allowed under ASTM D7467. For these B20 blends, the authors have also investigated the effects of biodiesel type upon criteria emissions, as well as the effects of base fuel type, the effects of engine technology, and the effects of test cycle.

Much less information is available regarding the impacts of biodiesel upon non-criteria emissions. However, the authors have compiled what they believe to be the most relevant information with respect to aldehyde emissions, PM number and size distributions, and PAH emissions. In addition, the authors have thoroughly investigated the issue of biodiesel's NOx effect, including explanations for its occurrence, the impacts of fuel properties and engine conditions upon the NOx effect, and mitigation measures taken to minimize the effect. All these topics are discussed below.

4.1 Data Selection Criteria

In the previous AVFL-17 project, published emissions results from nearly all sources were included and weighted equally. In this study, a more restrictive set of criteria was used to select the data included in the database that was developed to investigate impacts of biodiesel usage upon exhaust emissions. The selection criteria were similar to those used by EPA in their recent RFS2 Regulatory Impact Analysis. [9] The most significant criteria are the following:

- Use of a complete vehicle (for chassis dynamometer tests) or a multi-cylinder engine (for engine dynamometer tests) that is in commercial use. Generally, only HD engines of model year 1987 or later were included for data analysis. As exceptions, older engines were included when tested within a single study that also included testing of newer engines – such as Durbin et al.[124]).

- Use of standardized and well characterized test cycles. Emissions results obtained from a single steady-state operating condition were not included. However, established test cycles based upon a set of steady-state conditions were included.

- Use of biodiesel fuels (FAME) produced from commercially available vegetable oils or animal fats. This was restricted to canola, palm, rapeseed, soy, sunflower, tallow, and yellow grease; with rapeseed and soy being the dominant two feedstocks.

- Experiments in which a petroleum base diesel fuel was tested along with a biodiesel fuel (or blends of biodiesel). The petroleum base included conventional low sulfur No. 2 diesel (500 ppmS specification), ULSD (15 ppmS specification), CARB diesel (having both low sulfur and low aromatics), and other equivalent fuels.

4.2 Database Construction

The starting point for construction of the emissions database was a series of spreadsheets compiled by NREL researchers in their previous reviews on the topic of biodiesel emissions effects.[125,126] (Note: NREL has recently posted their HD engine/vehicle emissions database on their website.[127] To this body of data the authors added several more studies and deleted a few that did not satisfy the selection criteria given above. Compiled papers and reports were reviewed for emissions data, with all relevant information being added to the database. Appendix VII identifies all literature sources included in the emissions database, along with summary information about the engines, fuels, and test cycles used in each case.

Appendix VII is divided into three parts: (a) includes 50 references pertaining to HD/MD engine dynamometer tests, (b) includes 13 references pertaining to HD/MD chassis dynamometer tests, and (c) includes 20 references pertaining to LD chassis dynamometer tests. In all, these references include over 450 distinct emissions tests for all combinations of engines/vehicles, test cycles, biodiesel feedstocks, and after-treatment systems. Of these tests, approximately 250 involved HD engines using engine dynamometer testing, 80 involved HD engines/vehicles using chassis dynamometer testing, and 130 involved LD engines/vehicles.

The complete emissions database is structured as a spreadsheet that is provided in electronic form only. Each row in the database represents a single emissions test. The database includes the following fields of information:

A. Study ID-This is the original ID name used in the database acquired from McCormick and NREL.

B. Study ID- DRI's identifier for individual literature references

C. Ref. Number- Number assigned by reference manager to link the bibliography in the final report

D. Engine Year- The manufacturer's year of the engine that was tested for the accompanied emissions pollutants; if reported.

E. Engine Make- Manufacturer of engine used for the accompanying emissions; if reported.

F. Engine Model- Model name/number of engine used by the manufacturer for the accompanying emissions; if reported.

G. 2 or 4 cycle- Number of strokes the piston travels in each cylinder of the engine.

H. Catalyst- Was any type of catalyst used to treat the engine exhaust (Y/N).

I. Test Cycle- The load cycle applied to the engine's emissions testing.

J. Base Fuel- Base diesel fuel used for comparison during each study. Studies were only considered that used a comparison base diesel fuel in order to calculate emissions as a percentage change.

K. Biodiesel Fuel Source- The feedstock used to produce the tested biofuel.

L. Biodiesel Fuel Blend Level- The percentage of biofuel in base fuel used for emissions testing.

M. NOx % Change- Percentage change in NOx emissions from the referenced base fuel.

N. HC % Change- Percentage change in HC emissions from the referenced base fuel.

O. PM % Change- Percentage change in PM emissions from the referenced base fuel.

P. CO % Change- Percentage change in CO emissions from the referenced base fuel.

Q. CO_2 % Change- Percentage change in CO_2 emissions from the referenced base fuel.

R. Formaldehyde % Change- % change in formaldehyde emissions from the referenced base fuel.

S. Acetalaldehyde % Change- % change in acetalaldehyde emissions from the referenced base fuel.

T. Acrolein % Change- % change in acrolein emissions from the referenced base fuel.

U. Class- Engine's duty classification: Heavy-Duty/Medium Duty or Light-Duty

V. Engine or Chassis- Was the dynamometer used during emissions testing an engine dynamometer or chassis dynamometer.

In performing the analyses described in this section, the authors first computed the percent change in emissions when using biodiesel compared to a reference petroleum diesel fuel, rather than evaluating absolute emission rates. This approach helps to "normalize" the emissions results, and allows for clearer identification of fuel effects of specific biodiesel fuels and blends upon emissions. Publications that did not include a reference diesel fuel for comparison were not used to evaluate a percent change in emissions; although they are still listed in Appendix VII.

The emissions results from all tests, expressed as percent change from base, are shown in Appendix VIII. This appendix is also divided into three sections according to: (a) HD/MD engine dyno tests, (b) HD/MD chassis dyno tests, and (c) LD chassis dyno tests. Emissions changes are shown for the criteria pollutants (HC, CO, PM, and NOx; as well as for CO_2, though not all reports included CO_2 emissions results.

To assess changes in emissions with respect to the biodiesel blend fraction, the data were first segregated based upon engine type (HD/MD engine dynamometer, HD/MD chassis dynamometer and LD) and by emission species (HC, CO, PM, and NO_x). Table XII shows the number of test points included in the analyses of biodiesel emissions for each combination of engine and pollutant. In addition, this table shows the number of extreme outlier points that were eliminated from the analysis. These outliers were not defined by a rigorous statistical evaluation, but rather were identified by inspecting graphical displays of all results as a function of B-level for a single pollutant within a given engine/vehicle class (similar to

what is shown in Figure 11.) In general, results at a particular B-level that differed from the mean by over two standard deviations were identified as outliers.

Table XII. Number of Data Points used in Analysis of Biodiesel Emissions Effects

Engine/Vehicle Class	Pollutant	B20	B100	Other Blends	Outlier Points
HD/MD Engine Dyno	HC	103	59	66	2
	CO	104	62	43	3
	PM	106	59	40	2
	NOx	107	60	66	2
HD/MD Chassis Dyno	HC	43	22	19	0
	CO	39	21	19	3
	PM	39	22	19	0
	NOx	43	22	19	0
LD Engine and Chassis Dyno	HC	45	11	47	1
	CO	45	12	36	1
	PM	40	7	44	6
	NOx	45	10	46	3

As shown in Table XII, most emissions data were obtained from use of B20 and B100 fuels, although significant numbers of other blends were also reported. In addition, more data exist from HD engine dynamometer testing than from HD chassis or LD chassis dynamometer testing. In comparison with the previous analysis conducted under Project AVFL-17, this data set is considerably larger.

4.3   Impacts of Biodiesel Blend Level on Criteria Emissions

In their 2002 report, EPA concluded that use of biodiesel in HD diesel engines provided large emissions reductions for HC, CO, and PM as a function of B-level, but slight increases in NOx emissions. A graph taken from this report is included here as Figure 10.
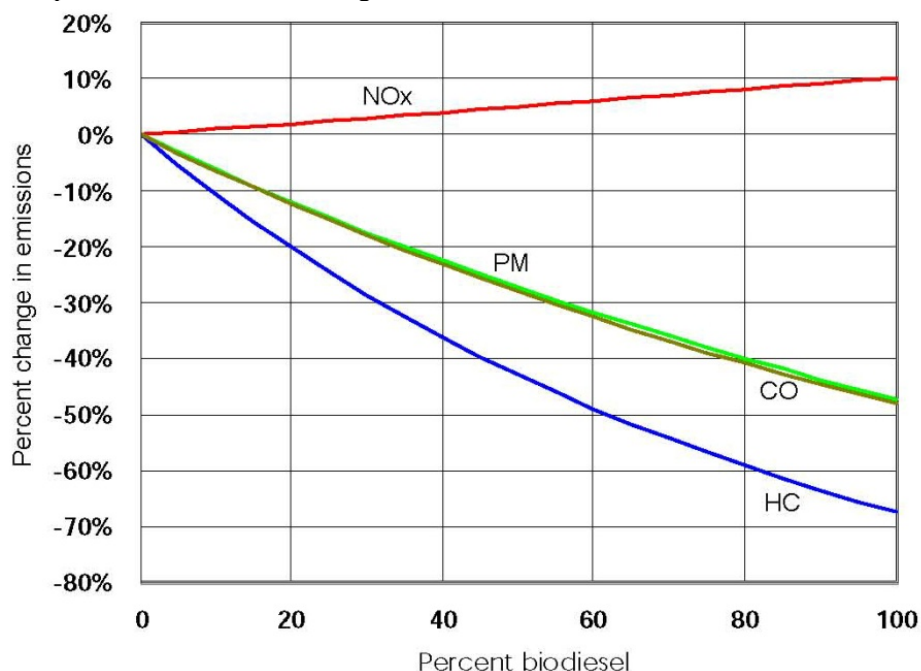
Figure 10. Average Emission Impacts of Biodiesel for HD Highway Engines (EPA, 2002)

In this AVFL-17a study, the authors have analyzed an extensive set of emissions data in a similar fashion, to investigate the impacts of B-level upon the same four criteria pollutants. The results are shown in a series of graphs comprising Figure 11. A separate page is used to show the results for: (a) HC, (b) CO, (c) PM, and (d) NOx. On each page, three graphs are included: the top panel shows results from HD/MD engine dyno tests, the middle panel shows results from HD/MD chassis dyno tests, and the bottom panel shows results from LD chassis dyno tests.

It should be noted that in this initial analysis, there was no differentiation among biodistillate feedstock type (i.e. soybean, rapeseed, palm, etc.), base fuel type, emissions test cycles, or engine model year. (These parameters are investigated later.) This inclusive approach was meant to show the wide range of emissions effects reported in the literature.

The graphs in Figure 11 show that considerable variability exists in the database. Before proceeding with further data analysis, these plots of emission impacts vs. biodiesel blend level were investigated for outliers. In general, data points greater than two standard deviations from the mean at a given B-level were eliminated, although a few additional points were also removed based upon professional judgment. The total number of outlier points for each pollutant and engine/vehicle class are shown in Table XII. All outlier points are also indentified in the electronic database and the appendix tables of this report.

Best fit logarithmic trend lines were also included on the graphs in Figure 11 to provide a point of comparison with EPA's reported effects, as shown in Figure 10. The best-fit curves and equations in black represent the logarithmic fit of the entire data set (excluding outliers) while the curves and equations in red represent only 4-stroke engines. Only one equation is shown for the light-duty graphs since these do not include any 2-stroke engines.

HC HD/MD Engine Dyno. Emissions

Legend:
- HC HD/MD Engine 2 Stroke
- HC HD/MD Engine Dyno. 4 Stroke
- Log. (HC HD/MD Engine Dyno. 4 Stroke)
- Log. (HC HD/MD Engine All)

$y = -19.37\ln(x) + 40.652$
$R^2 = 0.3981$

$y = -19.19\ln(x) + 40.067$
$R^2 = 0.3665$

HC HD/MD Chassis Dyno. Emissions

Legend:
- HC HD/MD Chassis 2 Stroke
- HC HD/MD Chassis Dyno. 4 Stroke
- Log. (HC HD/MD Chassis Dyno. 4 Stroke)
- Log. (HC HD/MD Chassis All)

$y = -28.61\ln(x) + 73.432$
$R^2 = 0.6154$

$y = -28.75\ln(x) + 72.865$
$R^2 = 0.6532$

HC LD Emissions

$y = -7.765\ln(x) + 15.663$
$R^2 = 0.0445$

(a) HC

Figure 11a,b,c,d. Effect of Biodiesel Blends on Exhaust Emissions

78

CO HD/MD Engine Dyno. Emissions

$y = -12.11\ln(x) + 21.407$
$R^2 = 0.3429$

$y = -11.98\ln(x) + 20.893$
$R^2 = 0.3315$

CO HD/MD Chassis Dyno. Emissions

$y = -14.76\ln(x) + 29.728$
$R^2 = 0.2783$

$y = -13.53\ln(x) + 23.271$
$R^2 = 0.2759$

CO LD Emissions

$y = 8.5842\ln(x) - 24.64$
$R^2 = 0.0738$

(b) CO

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(c) PM

NOx HD/MD Engine Dyno. Emissions

$y = 4.1314\ln(x) - 9.8887$
$R^2 = 0.2071$

$y = 4.4364\ln(x) - 11.446$
$R^2 = 0.2395$

NOx HD/MD Chassis Dyno. Emissions

$y = -3.278\ln(x) + 10.49$
$R^2 = 0.0691$

$y = -2.717\ln(x) + 7.6346$
$R^2 = 0.0636$

NOx LD Emissions

$y = 1.4246\ln(x) - 0.4628$
$R^2 = 0.0181$

(d) NOx

81
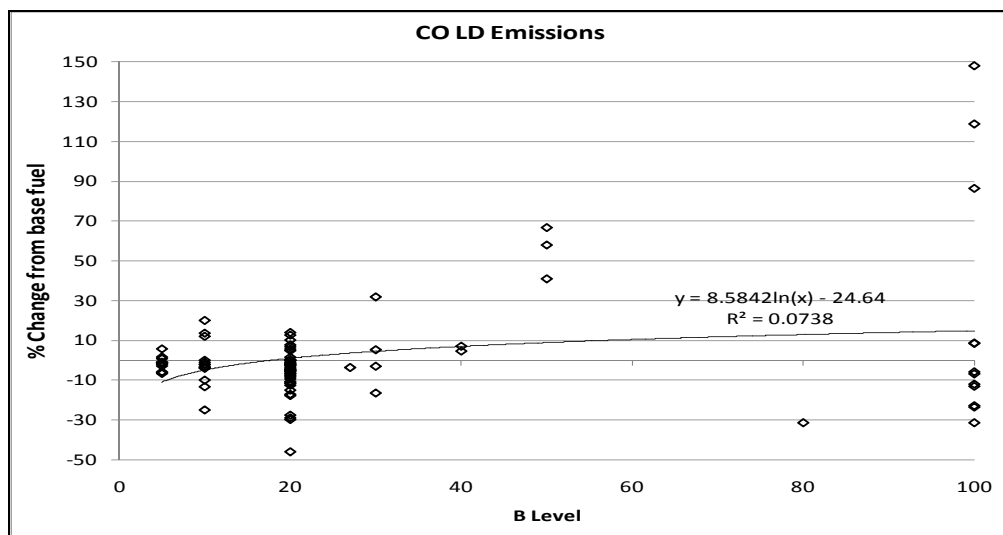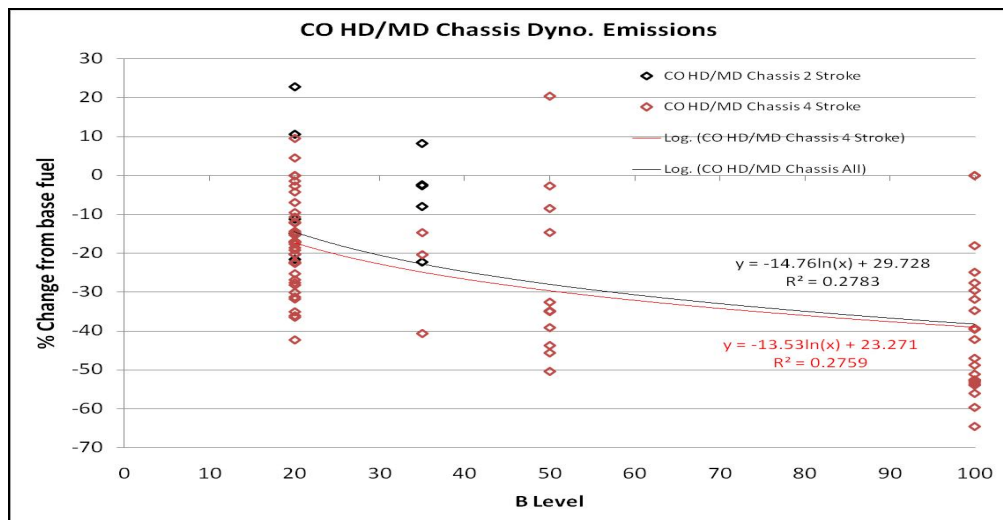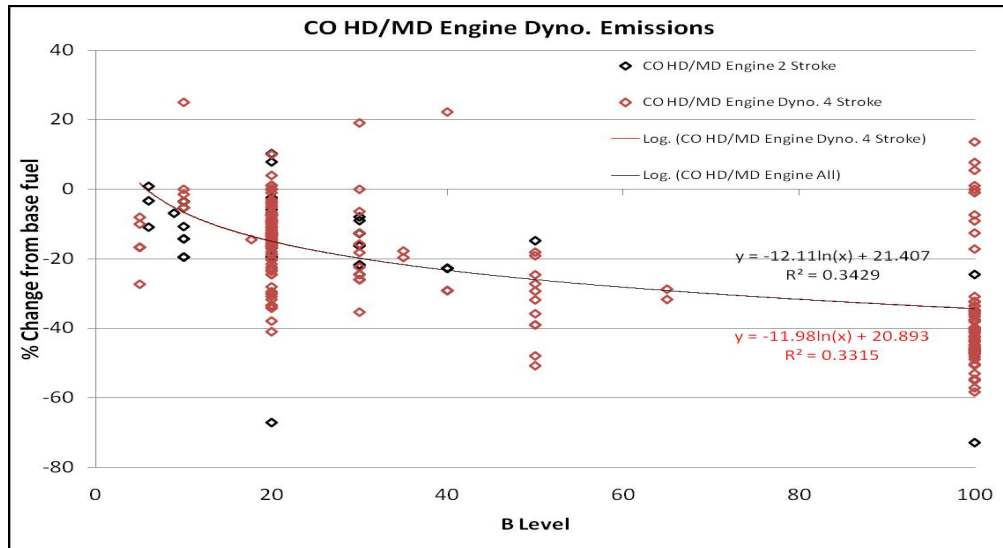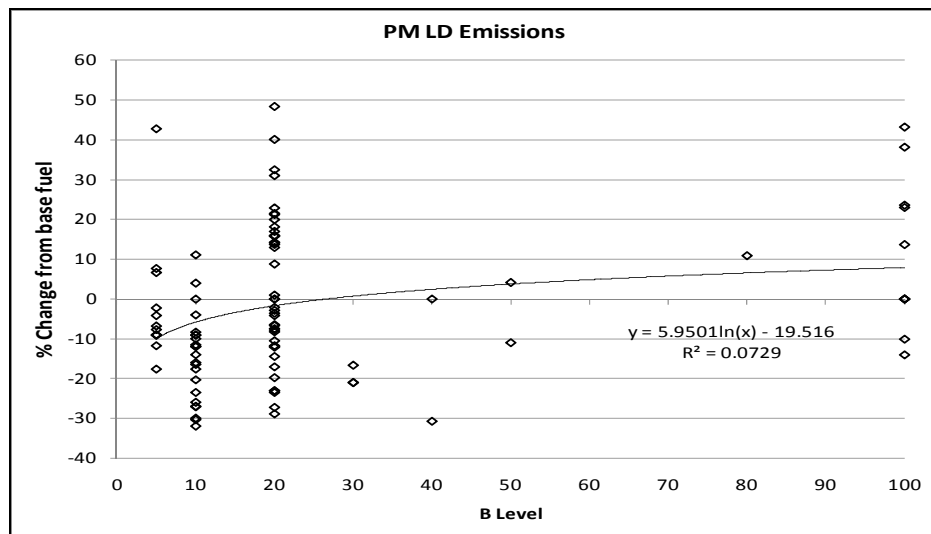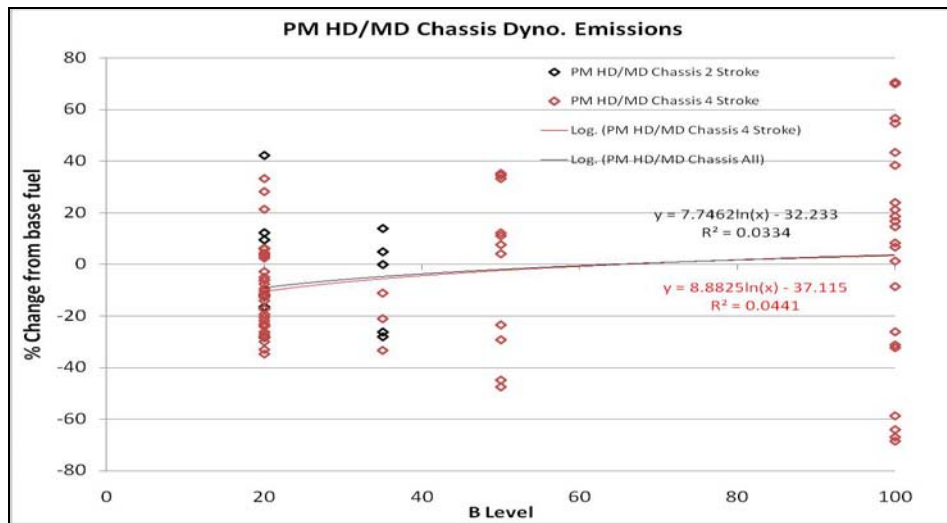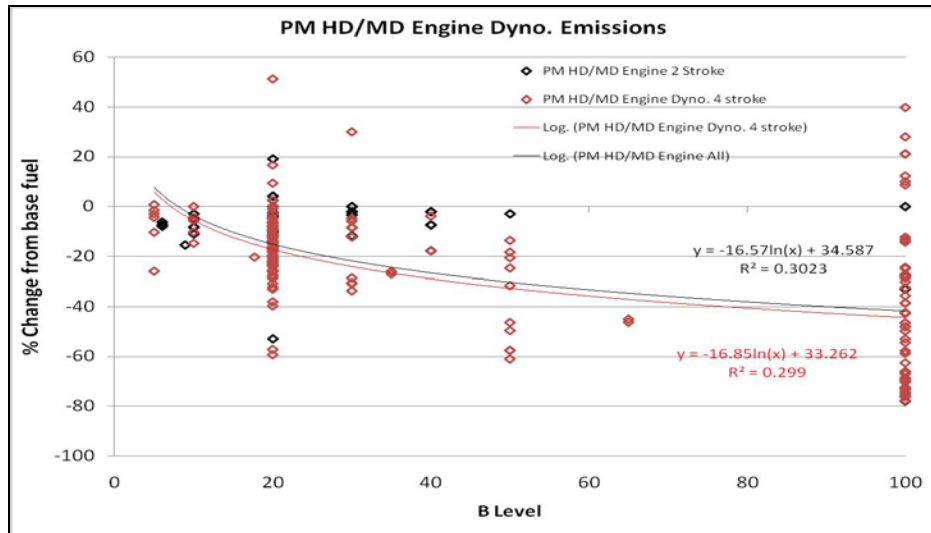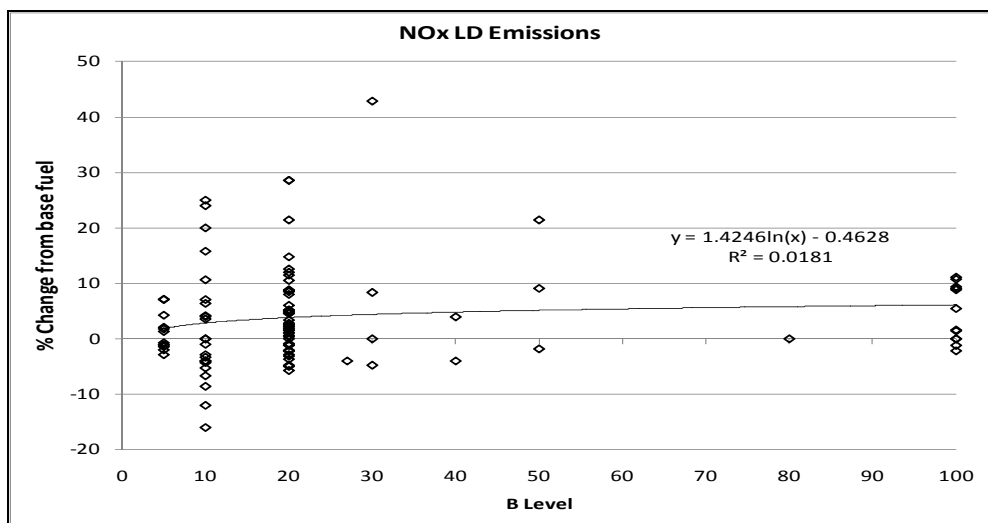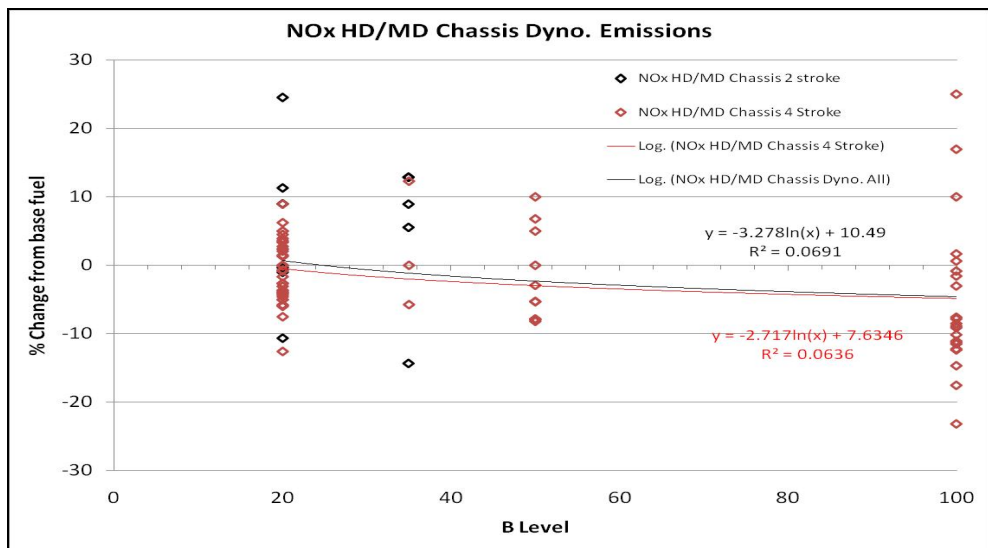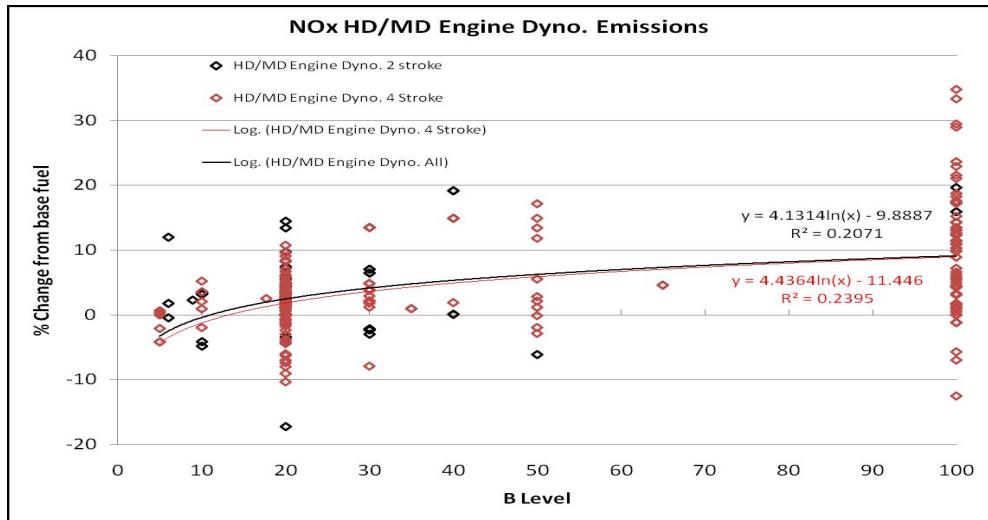
The logarithmic trend lines for Heavy-Duty 4-stroke engine dynamometer tests are compared with EPA's study from 2002 in Figure 12. In this figure each color corresponds to a specific criteria pollutant (HC, CO, PM, NOx). The solid lines represent EPA's results, while the dashed lines represent results for the current study. The NOx results of the current study are nearly identical to EPA's. For HC and CO, results from the current study are similar to EPA's at the B20 level, but show smaller benefit at the B100 level. For PM, results from the current study show slightly greater emissions reductions than EPA at the B20 level, but slightly lesser reductions at B100.
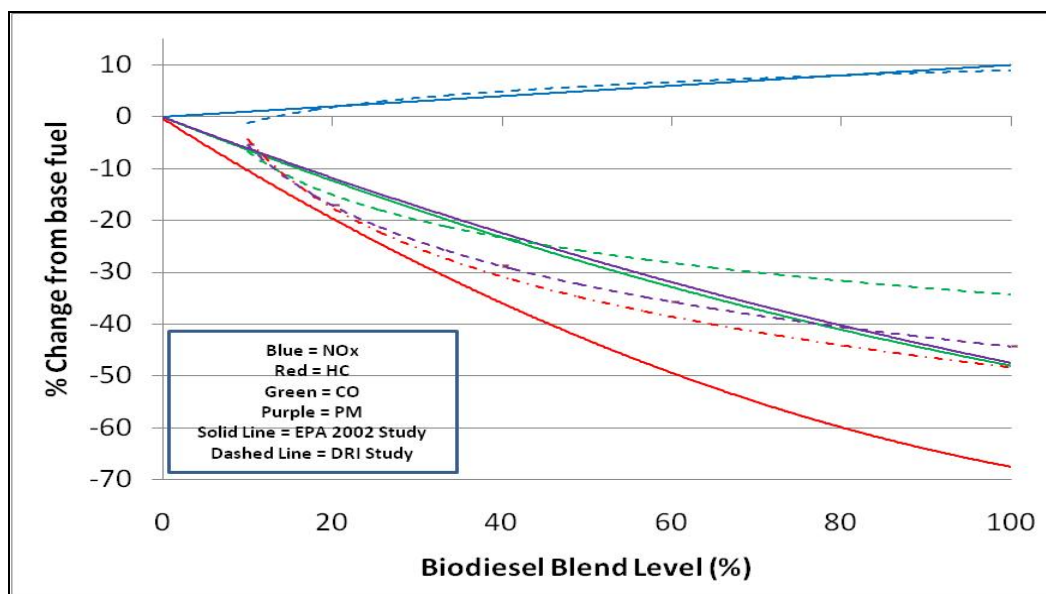
Figure 12. Emissions Effects of Biodiesel from HD Engine Dynamometer Tests
*DRI data from 4 stroke HD Engine Dynamometer tests only

The B20 and B100 emissions effects determined from these evaluations are summarized in Table XIII, which shows individual effects for each pollutant at each engine/vehicle testing type. As expected, the HD/MD engine dyno results show clear emissions reductions for HC, CO, and PM when using biodiesel; while the NOx effects are much smaller, and show a slight increase. The HD/MD chassis dyno results are quite similar for HC and CO, while opposite trends with increasing B-level are seen for PM and NOx. The LD emissions effects are small and variable.

Table XIII. Predicted Percent Change in Emissions using B20 and B100 in 4-Cycle engines (log fit)

Fuel	Pollutant	HD/MD Engine Dyno	HD/MD Chassis Dyno	LD Chassis Dyno
B20	HC	-17.4	-13.3	-7.6
	CO	-14.1	-17.3	+1.1
	PM	-17.2	-10.5	-1.7
	NOx	+1.8	-0.5	+3.8
B100	HC	-48.3	-59.5	-20.1
	CO	-34.3	-39.0	+14.9
	PM	-44.3	+3.8	+7.9
	NOx	+9.0	-4.9	+6.1

It should be emphasized that all these assessments include considerable variability, and that more sophisticated data analysis methods are required to determine the statistical significance of the results. However, of the three engine/vehicle testing types investigated here, the HD/MD engine dynamometer emissions set contains the most data, and appears to be the most robust.

A numerical comparison of the B20 emissions effects from different studies is provided in Table XIV. This shows that the effects determined by the current study all fall within the range of effects reported in the earlier studies. In large part, all these studies utilized similar emissions databases, although the specific data selection criteria and statistical methods differed somewhat.

Table XIV. Comparison of Average % Change in Emissions from HD Dynamometer Tests with B20

Pollutant	EPA (2002)	McCormick et al. (2006)	AVFL-17 (2009)	This Study
HC	-21.1	-11.6	-21.2	-17.4
CO	-11.0	-17.1	-18.7	-14.1
PM	-10.1	-16.4	-24.1	-17.2
NOx	+2.0	+0.6	-0.6	+1.8

4.4   B20 Emissions Impacts on Criteria Emissions (CO, HC, PM, NOx)

With B20 being the most frequently tested blend of biodiesel and also the highest concentration allowed by ASTM D7467, it was decided to investigate more closely the existing database for B20 emissions to determine whether additional insights could be gained. Only 4-cycle engines were compared for the following B20 analyses. Table XV provides the average changes in criteria emissions for the three different categories of engine/vehicle tests: HD/MD engine dynamometer, HD/MD chassis dynamometer, and LD chassis dynamometer. Also shown here are the number of data points used to compute each average and standard deviation. The mean and standard deviation results are also shown graphically in Figure 13.

Table XV. Average % Change in Emissions from B20 Dynamometer Tests

Engine/Vehicle Class	Pollutant	No. of Data Points	Mean	Std. Dev.
HD/MD Engine Dyno.	HC	83	-17.02	22.63
	CO	83	-14.66	10.00
	PM	85	-16.46	13.91
	NOx	86	1.41	3.97
HD/MD Chassis Dyno.	HC	38	-14.42	18.42
	CO	34	-18.77	12.01
	PM	34	-9.81	16.66
	NOx	38	-0.83	4.51
LD	HC	45	-8.64	28.19
	CO	45	-5.91	11.30
	PM	40	2.82	19.40
	NOx	45	4.40	7.74
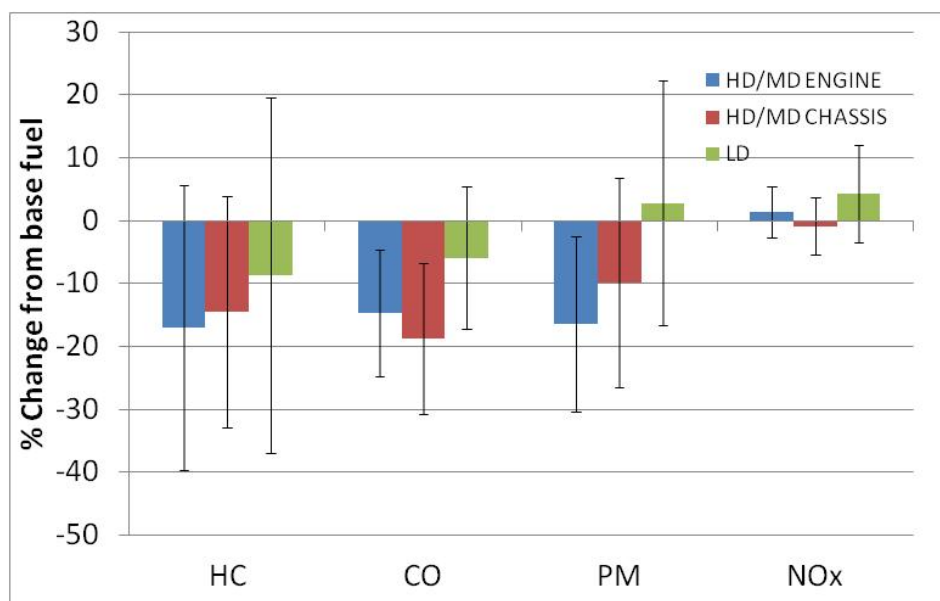
Figure 13. Average Impacts of B20 on Criteria Emissions (4-stroke engines only)
(Error bars represent one standard deviation)

4.4.1   Effect of biodiesel type

As shown below in Table XVI, soy is the most common biodiesel feedstock for B20 blends that have undergone emissions testing in both HD and LD applications. In this table, results from HD/MD engine dynamometer testing and HD/MD chassis dynamometer testing have been combined. (At the B20 level, the emissions results from engine dyno and chassis dyno are quite similar. Combining these two gives a more robust dataset.)

The results showing the effects of B20 feedstocks are also presented in Figure 14. As illustrated in this figure, there is a high degree of variability in the results, indicating that statistically significant differences are unlikely. Nevertheless, some interesting directional trends are suggested. For example, it appears that biodiesel from all feedstocks give substantial reduction benefits for HC, CO, and PM in HD/MD engines, while the NOx effects are small and uncertain. The most highly saturated feedstock, palm, appears to give a small NOx benefit, while the HC, CO, and PM benefits from palm-derived biodiesel may be somewhat smaller than from the other feedstocks. Soy-based biodiesel – which dominates the entire dataset – shows a slight NOx increase at the B20 level.

Table XVI. Average % Change in Emissions from B20 Dyno Tests – Effects of Biodiesel Feedstock
(4-stroke engines only)

Engine/Vehicle Class	Feedstock	Pollutant	No. of Data Points	Mean	Std. Dev.
HD/MD Engine + Chassis	Soy	HC	77	-13.65	23.34
		CO	74	-15.16	10.60
		PM	74	-15.09	15.44
		NOx	80	1.42	4.03
	Rapeseed	HC	17	-20.71	11.15
		CO	17	-17.05	12.16
		PM	17	-7.30	12.82
		NOx	17	-2.20	2.13
	Tallow	HC	10	-10.02	6.73
		CO	10	-7.91	4.57
		PM	10	-19.95	6.83
		NOx	10	1.58	3.01
	Yellow Grease	HC	9	-13.79	31.15
		CO	9	-7.17	13.13
		PM	9	-11.17	14.44
		NOx	9	0.12	5.34
	Palm	HC	1	-11.43	
		CO	1	-2.46	
		PM	1	-4.84	
		NOx	1	-3.00	
LD	Soy	HC	27	-1.82	26.20
		CO	27	-2.85	7.57
		PM	25	5.71	21.46
		NOx	27	2.20	4.03
	Rapeseed	HC	5	-31.33	29.73
		CO	5	-4.50	7.42
		PM	4	-3.64	19.66
		NOx	5	13.59	15.30
	Yellow Grease	HC	7	-23.73	30.54
		CO	7	-22.30	15.29
		PM	7	-3.87	10.77
		NOx	7	3.15	4.32
	Palm	HC	5	3.14	18.05
		CO	5	0.17	6.19
		PM	5	3.53	19.64
		NOx	5	5.43	8.70
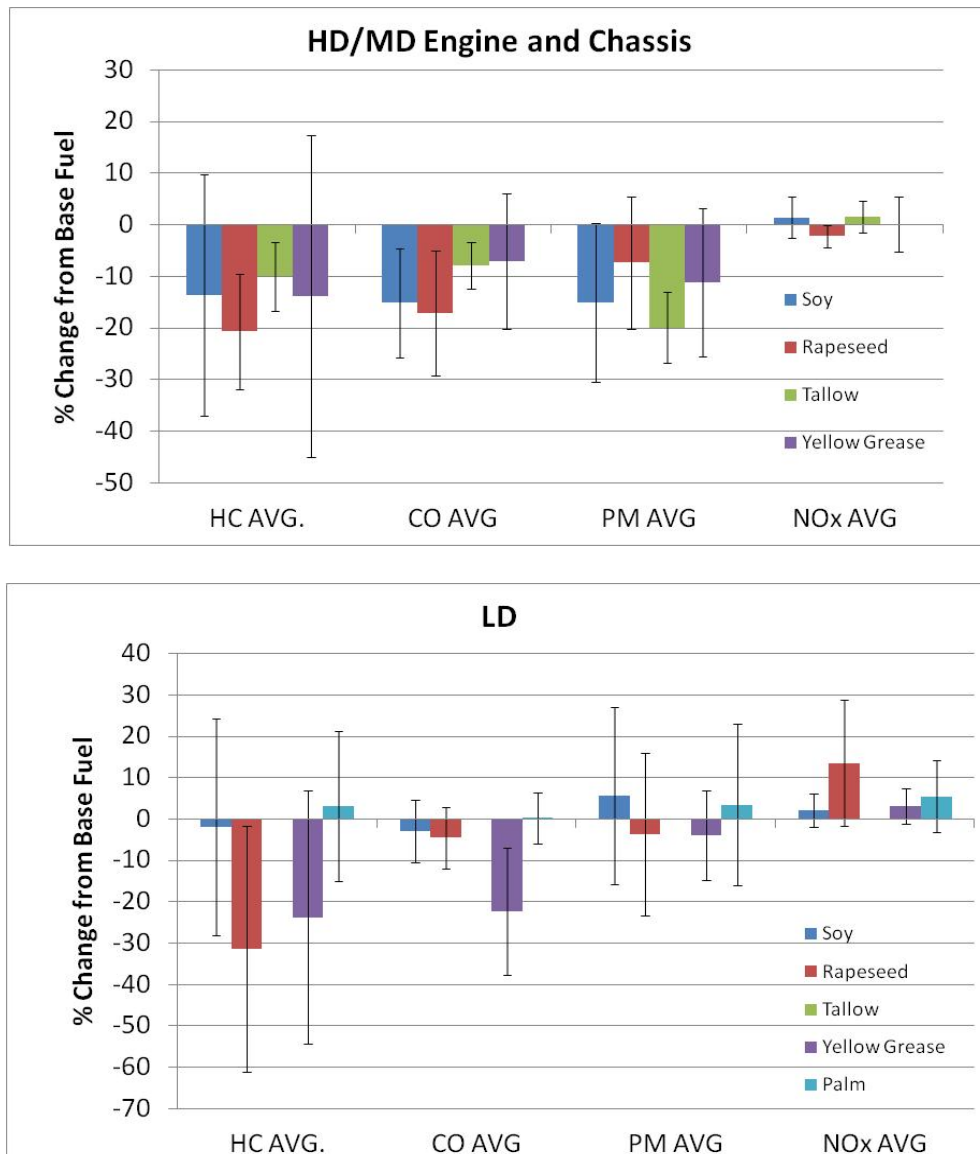
Figure 14. Impacts of B20 on Criteria Emissions - Effects of Biodiesel Feedstock: (a) HD/MD, (b) LD
(4-Stroke engines only; error bars represent one standard deviation)

4.4.2   Effect of Base Fuel

It has been suggested that the base fuel into which biodiesel is blended could have a significant effect on the changes in emissions results from use of B20. In this study, the authors classified all base fuels as one of three types: ULSD, CARB, and No. 2 DF. Different terminology is used by different researchers in describing the fuels they used. Because of this, the investigators applied their own judgment in assigning base fuel identities. The term "ULSD" was used to define any base fuel having reported sulfur levels less than 35 ppm. [Note: fuels meeting today's ULSD fuel standards have a maximum sulfur content of 15 ppm. In this study, the term "ULSD" is used to indicate fuels having sulfur levels substantially below those typically found in No. 2 DF, not to indicate fuels that fully comply with current ULSD requirements. A cutoff of 35 ppm was selected because this represents 10% of what was once considered "typical" for No. 2 DF.] The term "CARB" was used to identify a fuel said to comply with the California Low Aromatic Diesel (LAD) requirements, which also include ultra-low sulfur levels. The term "No. 2 DF"

was used to define all other base fuels. Many of these other base fuels were described in the literature as "low sulfur diesel" (LSD), or similar terms, but still had sulfur levels exceeding the 35 ppm cutoff.

As shown below in Table XVII, No. 2 DF was the most commonly used base fuel with the HD/MD engine class, while ULSD and CARB were more commonly used with the LD vehicles. These average results (with standard deviations) are shown graphically in Figure 15. This shows that use of biodiesel in CARB base fuel may provide somewhat lesser HC and CO emissions benefits in HD/MD engines compared to No. 2 DF or ULSD base fuels. However, due to the high variability, definitive conclusions are not possible. Also, the amounts of data in each base fuel category are very different, with fewer than 10 data points in the CARB set, and over 70 points in the No. 2 DF set.

Table XVII. Average % Change in Emissions from B20 Dynamometer Tests – Effect of Base Fuel

(4-Stroke engines only)

Engine/Vehicle Class	Base Fuel	Pollutant	No. of Data Points	Mean	Std. Dev.
HD/MD Engine + Chassis	No. 2 DF	HC	75	-19.11	19.70
		CO	76	-17.21	9.75
		PM	76	-14.34	12.61
		NOx	76	-0.16	3.92
	ULSD	HC	37	-13.22	22.83
		CO	35	-14.38	12.02
		PM	37	-14.56	20.08
		NOx	40	2.42	4.11
	CARB Diesel	HC	8	-2.65	24.78
		CO	6	-7.35	11.54
		PM	6	-17.05	6.51
		NOx	8	0.57	5.83
LD	No. 2 DF	HC	8	-5.88	17.89
		CO	8	-5.98	8.55
		PM	6	9.58	27.31
		NOx	8	-1.87	2.10
	ULSD	HC	16	-14.87	27.35
		CO	16	-2.21	7.12
		PM	13	-4.78	17.87
		NOx	16	8.99	5.83
	CARB Diesel	HC	21	-4.95	32.04
		CO	21	-8.71	14.08
		PM	21	5.60	17.21
		NOx	21	3.29	3.31
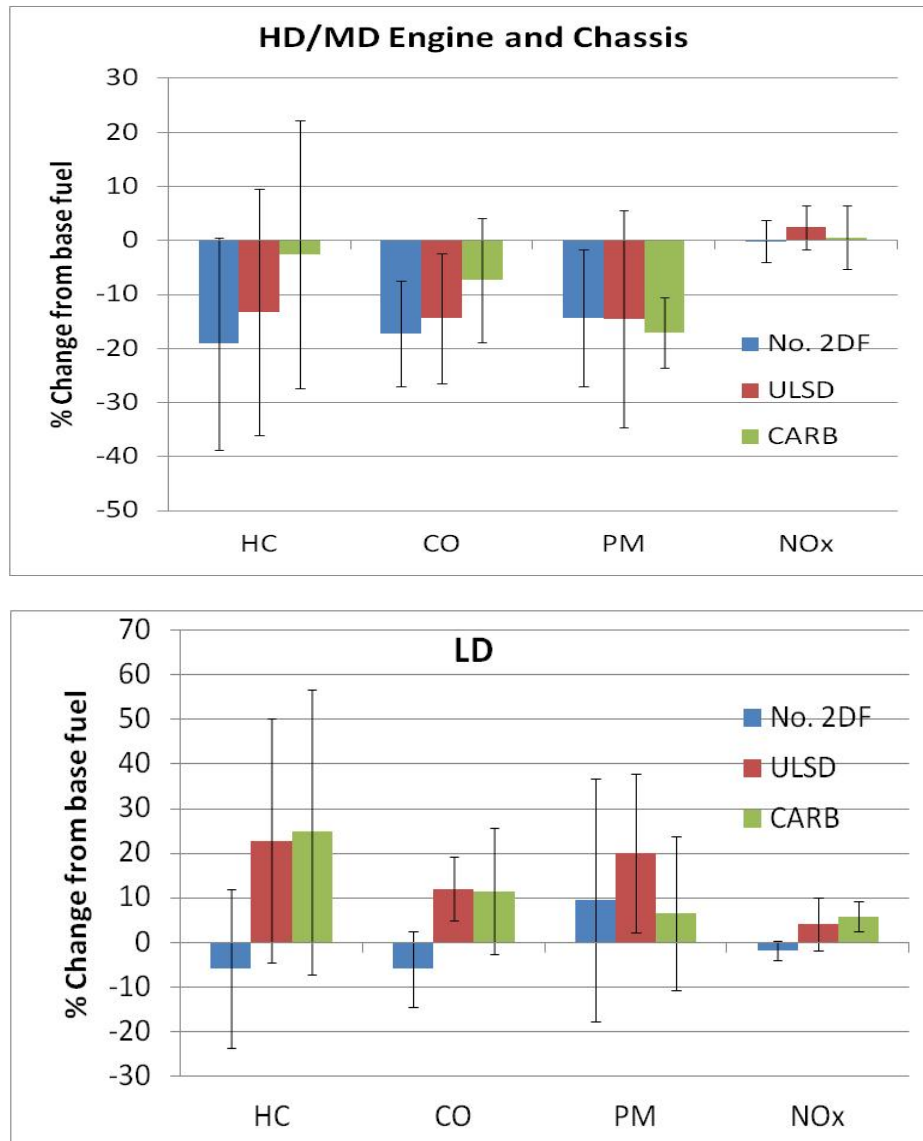
Figure 15. Impacts of B20 on Criteria Emissions - Effect of Base Fuel Type: (a) HD/MD, (b) LD
(4-Stroke engines only; error bars represent one standard deviation)

4.4.3   Effect of Engine Technology

Diesel engine technology has advanced greatly over the past two decades, driven in part by increasingly stringent emissions standards that have been applied. Table XVIII summarizes the evolution of the HD engine emission standards in the U.S. and Europe. It is conceivable that as engine technology changes, the response to use of biodiesel will also change. To investigate this, the emissions database was sorted by engine model year, and lumped certain time periods together to approximate changes in the HD NOx standard. The four time periods selected were as follows:

- 1987 – 1990:   NOx ≥ 6 g/bhp-hr
- 1991 – 1997:   NOx = 5 g/bhp-hr
- 1998 – 2003:   NOx = 4 g/bhp-hr
- 2004 – Present: NOx ≤ 2.5 g/bhp-hr

Table XVIII. HD Diesel Engine Emissions Standards – U.S. and Europe

Year	US Emission Levels, g/bhp-hr [1]			
	HC [2]	CO	NO_X	PM
1988	1.30	15.50	10.70	0.60
1990	1.30	15.50	6.00	0.60
1991	1.30	15.50	5.00	0.25
1994 [3]	1.30	15.50	5.00	0.10
1998	1.30	15.50	4.00	0.10
2004 [4,5]	0.50	15.50	2.50	0.10
2007 [6,7]	0.14	15.50	1.20	0.01
2010	0.14	15.50	0.20	0.01

[1] Based on U.S. EPA Transient Federal Test Procedure (FTP) engine dynamometer cycle. Useful life compliance period of 290,000 miles for HHDDE; 185,000 miles for MHDDE; 110,000 miles for LHDDE

[2] For 2004 and beyond, HC refers to non-methane hydrocarbons (NMHC)

[3] Maximum fuel sulfur level reduced to 500 ppm

[4] Optional standard of 2.4 g/bhp-hr for NMHC + NOx

[5] Venting of crankcase emissions prohibited except for turbocharged engines

[6] Additional requirements introduced for supplemental emissions test (SET)

[7] NO_x and PM standards phased-in between 2008 and 2010

Tier	Year	European Emission Levels, g/kw-hr [1]			
		HC	CO	NO_X	PM
Euro 1	1992	1.10	4.50	8.00	0.36 [2]
Euro II	1996	1.10	4.00	7.00	0.25
Euro III [3]	2000	0.66	2.10	5.00	0.10 [4]
Euro IV	2005	0.46	1.50	3.50	0.02
Euro V	2008	0.46	1.50	2.00	0.02
Euro VI	2013	0.13	1.50	0.40	0.01

[0] 1.0 g/kW-hr = 0.7457 g/bhp-hr

[1] Based on steady-state engine test ECE R-49 from 1992 to 1998. Based on European Stationary Cycle (ESC) and European Transient Cycle (ETC) in 1999 and beyond.

[2] PM allowed to 0.612 g/kW-hr for engines <85 kW

[3] Voluntary stricter limits apply for extra low emission vehicles known as "enhanced environmentally friendly vehicles" (EEV's)

[4] PM allowed to 0.13 g/kW-hr for engines with <0.75 dm^3 swept volume per cylinder

The number of data points, average emission results, and standard deviations for each pollutant and time period are shown in Table XIX. This information is also depicted graphically in Figure 16. These results suggest that engine technology has little impact upon the B20 fuel effects in HD/MD engines, with a possible exception of increasing PM reductions in advanced technology engines. However, it should be mentioned that relatively few engines/vehicles are included in the oldest and newest categories.

Table XIX. Avg. % Change in Emissions from B20 Dynamometer Tests – Effect of Engine Model Year (4-Stroke engines only)

Engine/Vehicle Class	Engine Year	Pollutant	No. of Data Points	Mean	Std. Dev.
HD/MD Engine + Chassis	1987-1990	HC	4	-14.38	4.80
		CO	4	-12.16	7.34
		PM	4	-6.74	7.18
		NOx	4	1.59	3.68
	1991-1997	HC	56	-19.72	22.64
		CO	56	-17.10	10.28
		PM	56	-12.49	13.18
		NOx	56	-0.30	4.45
	1998-2003	HC	38	-17.34	18.82
		CO	38	-16.26	11.17
		PM	40	-16.30	15.18
		NOx	41	2.65	4.33
	2004-Present	HC	23	-6.20	21.65
		CO	19	-12.16	11.45
		PM	18	-18.77	19.81
		NOx	23	2.65	2.97
LD	1987-1990	HC	16	5.31	33.74
		CO	16	-5.38	14.86
		PM	14	6.42	11.76
		NOx	16	1.44	2.89
	1991-1997	HC	7	-23.74	10.68
		CO	7	-12.72	7.97
		PM	7	5.93	27.63
		NOx	7	-0.22	4.54
	1998-2003	HC	12	-7.29	21.98
		CO	12	-0.57	6.11
		PM	12	-2.91	17.28
		NOx	12	4.77	7.20
	2004-Present	HC	4	-37.59	32.41
		CO	4	-7.13	8.56
		PM	1	-27.27	
		NOx	4	21.64	9.70
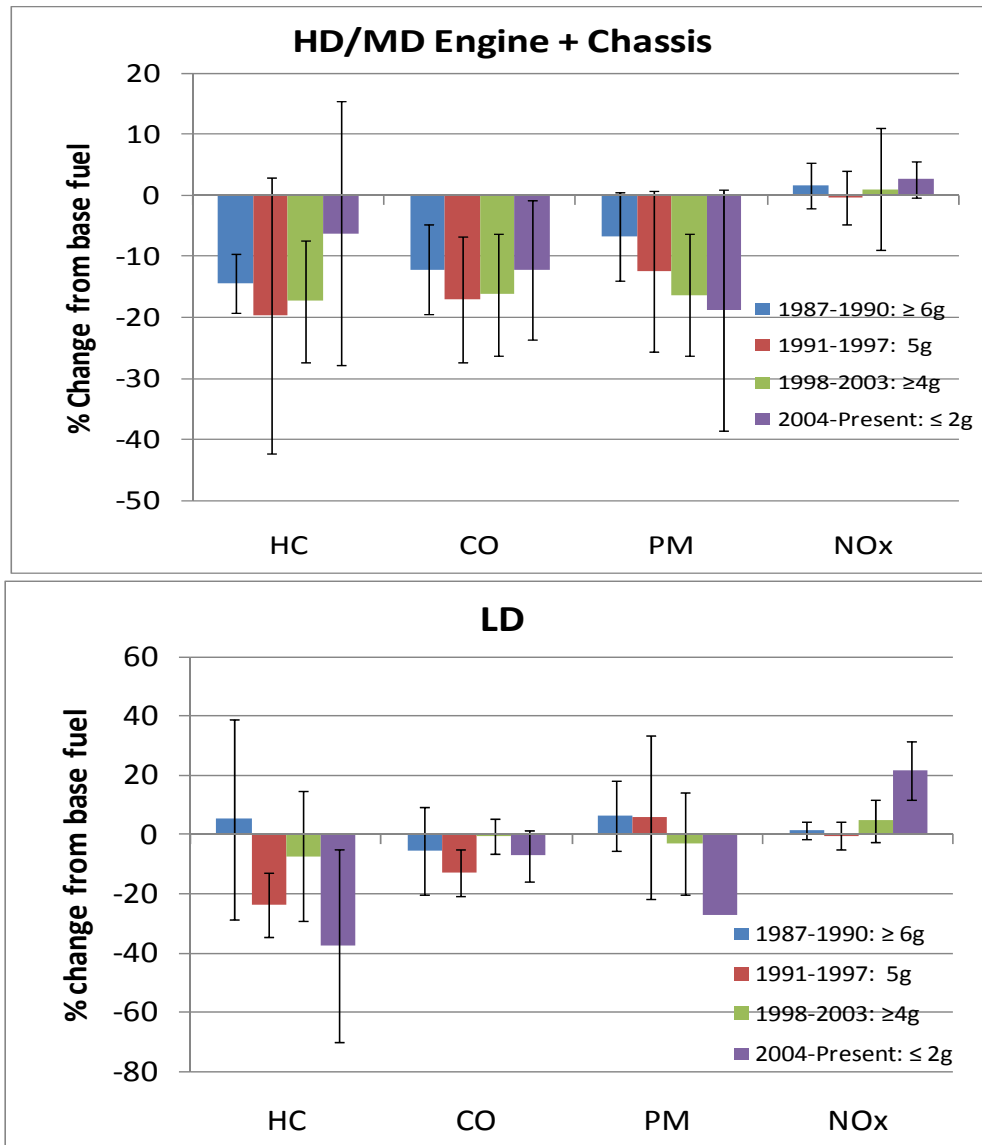
Figure 16. Impacts of B20 on Criteria Emissions - Effect of Engine Model Year: (a) HD/MD, (b) LD
(4-Stroke engines only; error bars represent one standard deviation)

4.4.4 Effect of Engine Load

To compare tests with similar engine loads, three different categories were chosen based on the approach in EPA's RFS2 regulatory impact analysis. The categories for Heavy-Duty engines were classified as: 5a-Light-Duty (Load) Cycle, 5b- Medium-Duty (Load) Cycle and 5c- Heavy-Duty (Load) Cycle. Only HD 4-stroke engine dynamometer tests were chosen for comparison. The EPA selected 8 cycles and two variations of a cycle to fit into these categories. From their study, additional cycles and operating conditions were considered, and placed into the applicable category in Table XX. Selection for each category was based on the average load throughout the cycle in comparison to cycles which EPA had previously chosen. The majority of load-cycles fall into the Medium-Duty (Load) category, as shown in Table XXI. It is difficult to compare to the Heavy-Duty (Load) Cycles as only one engine test fell into this category.

Table XX. Categories for Load Cycles using HD Engine Dynamometer Studies

Cycles	Case Description	Individual Cycles
5	Light-Load Cycles	CILCC, CSHVC, UDDS6k, *CBD
5b	Medium-Load Cycles	AVL8, Freeway, FTP, RUCSBC, UDDS, UDDS28k, *Arterial, ECER49, ETC, WHTC, ESC
5c	Heavy-Load Cycles	HWY55

*Black color indicates test cycles designated by EPA; red color indicates additional cycles designated by DRI.

Results from the assessment of engine load impacts on emissions are presented in Table XXI and Figure 17. Although it appears that NOx emissions may increase with engine test load, these results cannot be considered conclusive, due to the high overall variability, and the fact that a single test comprised the heavy load dataset.

Table XXI. Average % Change in Emissions from B20 Dynamometer Tests – Effect of Engine Load

Engine/Vehicle Class	Cycle Classification	Pollutant	No. of Data Points	Mean	Std. Dev.
HD/MD Engine + Chassis 4 cycle	5a (Light Load)	HC	11	-11.49	20.19
		CO	11	-14.60	9.82
		PM	10	-13.30	19.43
		NOx	11	-0.67	3.17
	5b (Medium Load)	HC	105	-16.95	21.77
		CO	102	-15.89	10.95
		PM	104	-14.40	14.67
		NOx	109	0.78	4.31
	5c (Heavy Load)	HC	1	-5.56	
		CO	1	-20.34	
		PM	1	-32.20	
		NOx	1	6.69	
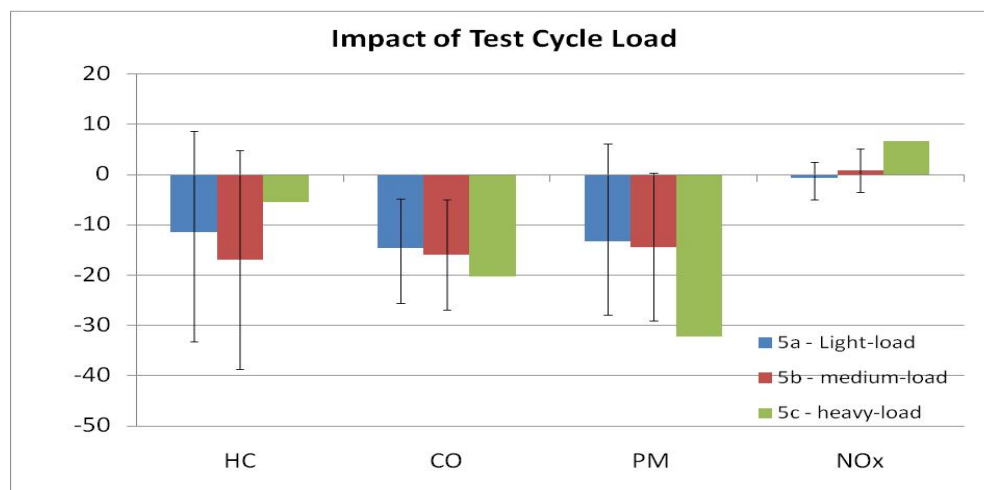
Figure 17. Impacts of B20 on Criteria Emissions - Effect of Engine Load
(Load categories from Table XX. 4-Stroke engines only; error bars represent one standard deviation)

4.5   Aldehyde Emissions

The issue of biodiesel's impacts on aldehyde emissions has been somewhat unclear and controversial. As shown in the sections above, the amount of aldehyde emissions data from well-controlled, laboratory dynamometer studies using established test cycles is very limited. However, there is considerably more information from non-standard test conditions. Much of this information is summarized in this section.

In a thorough review of the literature conducted in 2008, Lapuerta et al. identified approximately equal numbers of papers reporting increases and decreases in aldehyde emissions when using biodiesel.[128] However, several of the references cited used engines now regarded as obsolete, and fuels of questionable quality. In the present study, the authors limited their attention to newer technology, multi-cylinder engines (generally 1991 and newer) and to biodiesel blends that were reasonably well characterized and originated from common feedstocks.

4.5.1   HD Engines and Vehicles

In the 2003 NREL report on effects of biodiesel on HD diesel emissions, several neat biodiesel fuels and B20 blends (with LSD) were tested in a 1991 DDC Series 60 HD engine, using the U.S. HD Transient test cycle.[129] Although slight differences were seen, the authors concluded that aldehyde emissions were not significantly different between the biodiesel and base diesel fuel. In this study, proprionaldehyde was found to be the most abundant aldehyde, with acetaldehyde being second most abundant. At about the same time, Turrio-Baldassarri and co-workers tested a B20 blend of rapeseed-FAME in conventional diesel fuel using a Euro 2 HD bus engine and the European 13-mode cycle.[130] They found formaldehyde to be the most abundant aldehyde, with acetaldehyde being second most abundant. It was observed that formaldehyde increased 18% with B20, while total carbonyls increased 19%.

In 2004, Souligny et al. reported testing of B5 and B20 (from vegetable oil, tallow, and yellow grease) blended with conventional diesel fuel in 1998 and 2000 model year Cummins HD engines.[131] The U.S. HD Transient test cycle was employed. Results showed that in nearly every case, use of biodiesel gave lower aldehyde emissions. More recently, Correa and Arbilla reported testing of B2, B5, B10, and B20 in a 6-cylinder HD diesel engine typically employed in Brazilian buses.[132] The biodiesel was produced from castor oil, which has a composition quite different from most vegetable oils. In this study, all

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aldehydes were found to increase linearly with increasing B-level. Formaldehyde was the most abundant aldehyde.

Staat and Gateau provided a 1995 report on HD chassis dynamometer tests of French buses operating on rapeseed-derived B30 and B50.[133] The dominant aldehyde species observed with both the conventional diesel base fuel and the biodiesel blends were formaldehyde, acetaldehyde, and acrolein. Results showed that use of B30 had very little impact on these aldehydes, but that B50 caused slight increases in formaldehyde and acetaldehyde (~10%), and larger increases for acrolein (~50%).

In 2009, Lin et al. reported testing of palm-based biodiesel blends in a 6-cylinder Mitsubishi HD engine operating at a single, low-load condition.[134] Formaldehyde comprised over 70% of total aldehydes from both the base fuel (ULSD) and all biodiesel blends. Relative to the base fuel, formaldehyde increased with both B20 and B100 cases. However, when blending the palm-FAME into a highly paraffinic fuel, aldehyde emissions were reduced compared to the ULSD base fuel. Very similar results were obtained from a subsequent study in which the same engine and fuels were used, but the U.S. HD Transient test cycle was employed.[135]

Cheung and co-workers used a modern 4-cylinder HD diesel engine usually found in Hong Kong trucks to test blends of yellow-grease-derived FAME in ULSD, at oxygen contents of 2, 4, 6, and 8% (roughly B20 to B80).[136] Several steady-state modes were used. Results showed that formaldehyde and acetaldehyde were the dominant aldehyde emissions. Formaldehyde was found to increase with engine load, but decrease with B-level. In contrast, acetaldehyde decreased with load, but increased with B-level. Similar, but not identical results were reported by this same research group when using ULSD-biodiesel blends in comparison with ULSD-ethanol and ULSD-methanol blends.[137,138]

Also in 2009, Liu and co-workers reported testing a series of palm-based biodiesel blends (B10, B20, B50, B75, and B100) in a 2003 diesel engine/generator set operated at three load levels.[139] An extensive set of carbonyl compounds was measured, using DNPH impinger solutions. The dominant carbonyls observed were formaldehyde, acetaldehyde, acrolein, and acetone. Total carbonyl emissions decreased dramatically with engine load. This was attributed to higher exhaust temperatures at high load, which disfavor the presence of carbonyls. Lesser impacts were seen with changes in B-level. Addition of biodiesel did increase total carbonyls slightly, but not in proportion to the B-level.

Guarieiro and co-workers compared two different sampling methods for collecting carbonyls in diesel engine exhaust: DNPH dry cartridges and DNPH impinger solutions.[140] They demonstrated much higher carbonyl recoveries (3-5 times) with impingers compared to cartridges. This is surprising, and somewhat concerning, as DNPH cartridges have been widely used by many researchers in this area. Guarieiro also investigated a series of soy biodiesel blends (B2, B5, B10, B20, B50, B75, and B100) in a small 2-cylinder stationary diesel engine operated at a single steady-state mode. Acetaldehyde was the most prevalent aldehyde seen, followed by formaldehyde, proprionaldehyde, and acrolein. Low levels of biodiesel (B2-B10) increased formaldehyde slightly, but higher levels (B20-B100) resulted in decreased formaldehyde compared to the base No. 2 diesel fuel. Acrolein was found to increase substantially (100-300%) at all B-levels, while all other aldehydes decreased with B-level. In subsequent work, this research group employed the same 2-cylinder stationary engine, but used a variety of engine load settings and numerous fuel blends -- including alcohol-containing ternary blends.[141] Results were mixed, but most biodiesel-containing fuel blends were found to increase aldehyde emissions. Again, the increase in acrolein was most significant.

In 2009, He and co-workers published their investigation of aldehyde emissions from use of soy-based biodiesel (B100) in a 4-cylinder, HD Chinese diesel engine.[142] The base fuel was conventional No. 2 diesel fuel; the test cycle was the 8-mode ISO 8178 Type C1. The dominant aldehyde emission species

from both fuels were formaldehyde, acetaldehyde, and acrolein/acetone. When weighted over the 8-mode cycle, total carbonyl emissions were nearly 3 times higher from the B100 fuel compared to base fuel.

Lea-Langton and co-workers used an FTIR method for real-time detection and quantification of gaseous emissions species – including aldehydes – from a Euro 2 Perkins Phaser HD engine.[143] Both B100 (from yellow grease) and ULSD were used at two steady-state operating conditions. Formaldehyde was the most abundant aldehyde species, followed by acrolein and acetaldehyde. Distinct concentration peaks for each aldehyde was seen during cold-start operation, with lower emission levels after warm-up. No significant differences in aldehyde emissions were observed between B100 and the ULSD base fuel.

Koszalka et al. also conducted real-time FTIR measurements of aldehydes.[144] A 4-cylinder diesel engine typically found in Polish delivery vans was used with B50 and B100 (undefined feedstock) along with a No. 2 diesel base fuel. When operating under full load steady state conditions, B100 produced considerably higher formaldehyde and acetaldehyde emissions than base fuel, with B50 giving intermediate results. However, when using the 13-mode ESC cycle, B100 gave only slightly higher formaldehyde and acetaldehyde than base, while B50 gave lower aldehyde emissions than base.

An FTIR method was also used by Fisher et al. in characterizing aldehyde emissions from a 2003 John Deere 4024T engine.[145] This engine was operated at two steady-state modes, using B20 and B100 from soy, canola, and two custom blends meant to represent algal compositions. Both formaldehyde and acetaldehyde were measured. Results were somewhat mixed, with no large changes (>20%) observed for either aldehyde under any operating condition. In most cases, formaldehyde emissions from soy and canola B20 and B100 were slightly lower than from ULSD base fuel, while emissions from the algal fuels were slightly higher than from base. Acetaldehyde emissions from all the biodiesel blends were about 20% lower than from ULSD base under low load conditions, but showed smaller reductions at high load.

4.5.2   LD Engines/Vehicles

Peng and co-workers conducted engine dynamometer tests using a 2.8L, 4-cylinder Mitsubishi engine, typically found in Taiwanese pickup trucks.[146] The U.S. LD Transient cycle was used with B20 (from yellow grease) and ULSD base fuel. Formaldehyde and acetaldehyde were the dominant aldehyde species observed, with lesser amounts of proprionaldehyde and acrolein. Compared to base fuel, B20 resulted in about 20% reduction in formaldehyde, with no significant change for the other species. It was also observed that aldehyde emissions did not significantly change with increased engine mileage, from 0 to 80,000 km.

In a recent series of papers, a research group consisting of Karavalakis, Stournas, Bakeas, and others has published results from extensive testing of biodiesel blends in LD passenger cars, using several different driving cycles. Karavalakis et al. described testing of a 1998 Euro 2 Toyota using the New European Driving Cycle (NEDC) and the Athens Driving Cycle (ADC).[147] Both palm-FAME and rapeseed-FAME blends in LSD were used (B5, B10, and B20). Of the 13 carbonyl compounds measured, formaldehyde, acetaldehyde, proprionaldehyde, and crotonaldehyde were the most abundant. Formaldehyde was found to increase with B-level under both driving cycles. Acetaldehyde decreased with B-level of palm-FAME, but showed mixed results with rapeseed-FAME. Additional testing of the same vehicle (and same driving cycles) with soy-derived biodiesel (B5, B10, and B20) gave quite different results.[148] In this case, both formaldehyde and acetaldehyde emissions decreased with B-level under both driving cycles.

Testing of a different Euro 2 vehicle (VW Golf 1.9 TDi) with soy-derived FAME (B100) was conducted by the same research group.[149] The NEDC was used, along with a more realistic driving cycle called

the Artemis cycle. Compared with the low sulfur base fuel, use of B100 dramatically increased most aldehyde species, under both driving cycles.

Another publication by this group reports testing of a 2003 Euro 3 Toyota vehicle using the NEDC and ADC driving cycles.[150] In this case, palm-derived FAME was used in LSD at levels of B5, B20, and B40. Formaldehyde, acetaldehyde, and crotonaldehyde were the dominant aldehyde species observed, along with significant amounts of benzaldehyde, methacrolein, and hexanaldehyde. The emissions rates of acrolein/acetone were very low, and below detection limits in several cases. Changes in aldehyde emissions with increasing B-level were inconsistent, with some species increasing and other species decreasing. Results between the two driving cycles were also inconsistent.

Another Euro 3 vehicle (Renault Laguna 1.9 dCi) was tested over the NEDC and Artemis driving cycles using five different B10 blends: rapeseed, sunflower, soybean, palm, and yellow grease.[151] In all cases, the dominant aldehyde species were formaldehyde, acetaldehyde, and acrolein/acetone. While overall, these low level blends had only small effects on aldehyde emissions, differences among the biofuel types were evident. Under both driving cycles, generally higher aldehyde emission rates were seen from the palm-, rapeseed-, and sunflower-derived FAME as compared to the LSD base fuel. The soy- and yellow grease-derived FAME blends gave somewhat lower aldehyde emissions compared to base fuel.

The same research group tested a Euro 4 LD vehicle (2007 Subaru Forester) over the NEDC and Artemis driving cycles using soy-derived and yellow grease-derived FAME.[152] B20, B30, and B50 blends of each type in a ULSD base fuel were used. Formaldehyde, acetaldehyde, acrolein/acetone, and proprionaldehyde were the dominant aldehyde species observed. Results from both driving cycles showed clear increases in all aldehydes with increasing B-level. Also, somewhat higher emission rates were observed from the NEDC cycle compared to the Artemis cycle.

Finally, Karavalakis et al. reported on testing another Euro 4 LD vehicle (Hyundai Santa Fe 2.2 VGT) over the NEDC and Artemis cycles using soy-derived FAME at B10 and B30 levels in ULSD.[153] Most aldehyde species – especially formaldehyde and acetaldehyde – were found to increase with increasing B-level, on both driving cycles. The effect of driving cycle was also apparent, with aldehyde emissions being highest under the cold-start NEDC and the Artemis Urban cycles.

4.5.3 Biodiesel Impacts on Aldehyde Emissions

Aldehyde emissions results from the above-discussed studies (and other studies) were collected for formaldehyde, acetaldehyde, acrolein and total aldehydes. A separate aldehyde emissions database was constructed, as shown in Appendix IX for three engine test classifications, (1) Heavy-Duty engine dynamometer tests, (2) Light-Duty engine dynamometer tests; and, (3) Light-Duty chassis dynamometer tests. Due to the lack of data, outliers were not removed and steady-state tests were included.

Emissions results from all these engine test classifications are shown in figure 18 (a) formaldehyde, (b) acetaldehyde, (c) acrolein and (d) total aldehyde. While there are some data suggesting that aldehyde from LD would increase with use of biodiesel, the overall variability is so large that no firm conclusions can be made. It should be pointed out that many of the extreme results shown in Figure 18 originated from just two studies: Study No. 1 involved testing of a LD engine with palm-based biodiesel over a custom test cycle. This study was reported in 2009 by Yu-Yin et al. [139] Study No. 2 involved testing of a LD vehicle with rapeseed-based biodiesel over a test cycle meant to represent driving patterns in Athens. This study was reported in 2009 by Karavalakis et al. [148]

Several factors may contribute to the overall high variability in the aldehyde emissions database. First, the database is relatively small, but contains results from a wide variety of engine/vehicle types and test

cycles. Second, different methods for sampling and analysis of aldehydes are included in the database – although sampling with DNPH cartridges, followed by HPLC/UV-vis analysis is most common. Third, a variety of biodiesel fuels (of unknown quality) were used. It is thought that minor impurities such as methanol, glycerine, and monoglycerides can contribute to aldehyde emissions.
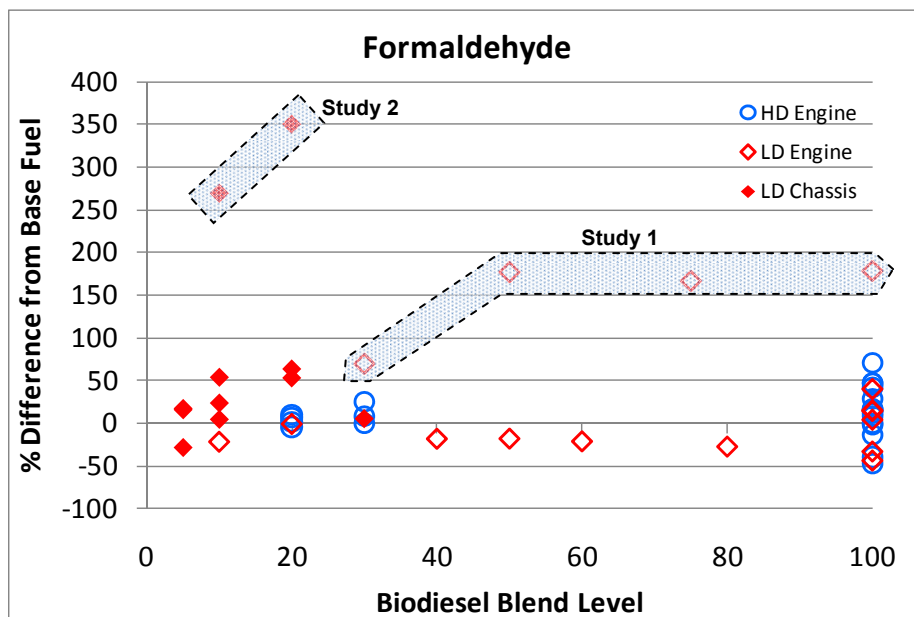
(a)
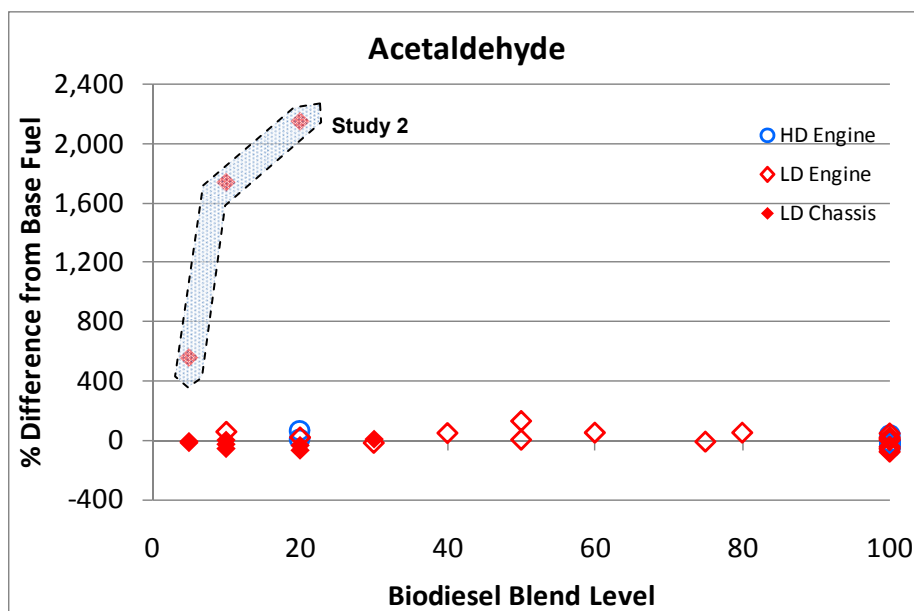
(b)

Figure 18. Impacts of Biodiesel Blend Level on Aldehyde Emissions: (a) Formaldehyde; (b) Acetaldehyde; (c) Acrolein; (d) Total Aldehydes.
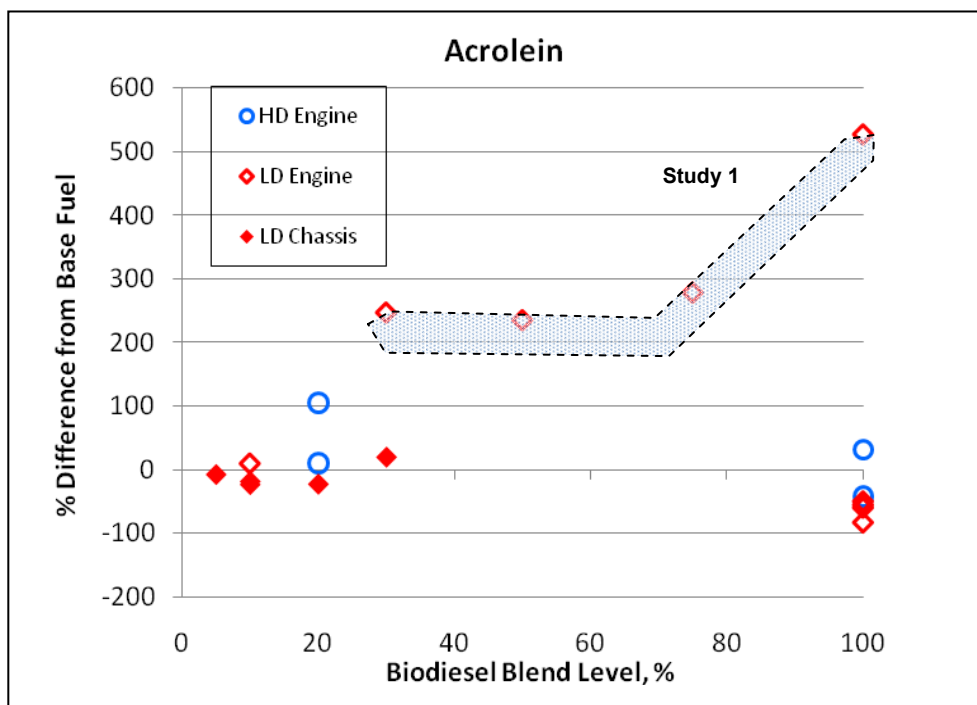
(c)
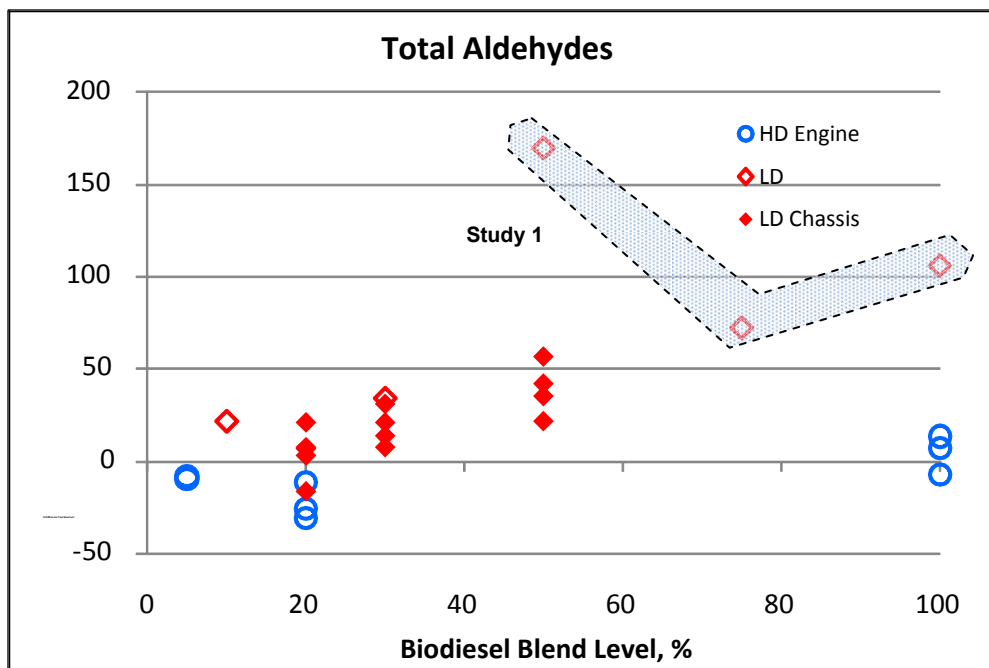
(d)

4.6 Particle Number and Size Distributions

It is now firmly established that use of biodiesel has a beneficial effect of reducing total PM emissions in nearly all situations. However, there is growing interest in understanding how biodiesel may influence the number and size distributions of the PM. In particular, there is concern that while total particle mass may be reduced when using biodiesel, the number of small particles may increase.

Particle size distributions are characterized differently within different scientific communities. Typically, the term "fine particles" is used when referring to $PM_{2.5}$, meaning particles having mean aerodynamic diameters of 2.5 μm and smaller. The term "ultrafine particles" is often used to refer to $PM_{1.0}$; meaning particles having diameters of 1.0 μm (1000 nm) and below. Within the automotive emissions community, it is also common to distinguish particles according to their formation origin. The term "nucleation mode particle" is used to define the very small particles (typically < 20 nm) arising from initial soot formation; exhausting of metallic compounds; and condensation of sulfuric acid, lube oil, and heavy unburned fuel constituents. (The terms "nanoparticle" and "nucleation particle" are sometimes used interchangeably.) The term "accumulation mode particle" is used to refer to larger particles (typically 30-200 nm) arising from soot agglomeration and adsorption of organics onto the soot agglomerates. In most cases, the majority of ultrafine particle numbers is in the nucleation size range, while the majority of ultrafine particle mass is in the accumulation size range. Several excellent reviews on the topic of particulate emissions from diesel engines have appeared recently, which also provide a good basis for understanding these issues with biodiesel emissions.[154,155,156]

In a recent study by Tan et al., an Engine Exhaust Particle Sizer (EEPS) instrument was used to characterize the particle size distributions arising from use of jatropha-derived FAME in a modern LD diesel engine, while operating under a variety of steady-state modes.[157] It was observed that as the B-level increased, the number of accumulation mode particles decreased (hence total mass decreased), while the number of nucleation mode particles increased (hence total particle numbers increased). One reason suggested for this increase in nucleation particle numbers with biodiesel is the low volatility of the jatropha-FAME, resulting in greater formation of condensation particles – similar to nucleation particle formation from lube oil.

Using a series of individual FAME compounds in a single-cylinder test engine, Schonborn and co-workers demonstrated a relationship between fuel boiling point and the number of nucleation mode particles.[158] This was taken as evidence that a large proportion of total nucleation mode particles from biodiesel combustion may consist of condensed liquid fuel droplets. These researchers also investigated biodiesel fuels produced from four different feedstocks: rapeseed, palm, tallow, and jatropha. Of these four, jatropha-derived FAME produced the largest number of nucleation mode particles. This was attributed to the presence of the high molecular weight species, lignoceric acid (C24:0) methyl ester present in jatropha-FAME.

Using a 2.5L DDC LD diesel engine, Boehman's research group at Penn State University investigated the impacts of fuel injection phasing on engine operation and emissions when utilizing biodiesel (soy-FAME) and other alternative fuels.[159,160] Consistent with previous literature reports [161,162], they demonstrated that fueling with B100 generally resulted in a slight decrease in mean particle diameter. [Only a single size mode could be measured with the scanning mobility particle sizer (SMPS) used in this study.] These researchers also demonstrated that the B100 particles consisted largely of condensed organics that could be readily driven off when using a thermal denuder to heat the exhaust samples. It was also shown that when using certain injection strategies, use of biodiesel actually increased total PM mass emissions.

Lapuerta et al. used a modern 2.2L Nissan LD diesel engine to investigate the impacts of biodiesel (yellow grease FAME) upon PM emissions.[163] B30, B70, and B100 were used under five steady-state operating modes. It was shown that increasing B-level reduced total PM mass emissions substantially, and reduced particle mean diameter slightly (from about 105 nm to 80 nm). This decrease in particle size was thought to be due to preferential reduction of the larger particles within the normal size distribution from diesel fuel, not due to formation of additional small particles with use of biodiesel. Similar results under the same experimental conditions were reported later by this research group when using soy- and tallow-based biodiesel.[164] (Note: the SMPS instrument used in these studies is not able to measure nucleation mode particles below about 20 nm.)

Similar results were observed by Chien et al. who investigated the use of biodiesel (from yellow grease) in a 6-cylinder LD Mitsubishi engine operated under the U.S. FTP Transient test cycle.[165] A MOUDI and nano-MOUDI instrument were used together to collect 13 size ranges of PM, which were then combined and classified into 4 size groups. Increasing B-level in the fuel was found to shift the distributions towards the smaller size groups, mainly by reductions in the numbers of particles in the larger size groups.

A modern, Euro III, HD diesel engine was used by Krahl and co-workers to investigate ultrafine particles emissions from B100 (rapeseed-FAME) compared to ULSD.[166] When sampling diluted exhaust at 20°C, biodiesel produced lower numbers of particles in the 30-300 nm range compared to ULSD, but higher numbers in the 10-20 nm range. With heated samples (250°C), the biodiesel emissions no longer had higher particle numbers in the 10-20 nm range, but the reduction in particles at 30-300 nm persisted. The authors concluded that the smallest size particles from biodiesel consist of condensed, unburned fuel This is consistent with earlier work by the same research group who showed that the soluble fraction of collected PM is higher with biodiesel, while the insoluble fraction is higher with conventional diesel fuel.[167]

Fontaras and co-workers investigated a set of five different B10 blends in ULSD (rapeseed, palm, soybean, sunflower, and yellow grease).[168] A Euro 3 Renault vehicle was tested over several different dynamometer driving cycles. Results showed that all five B10 fuels reduced total PM in all cases, and reduced the number of non-volatile particles in most cases. (Non-volatile particles numbers are important because European emission regulations will soon impose emission limits.) Total particle numbers (both volatile and non-volatile) were more variable with biodiesel type and driving cycle. In particular, it was noted that use of rapeseed-FAME gave higher total particle numbers than base fuel.

Heikkila et al. used a Euro IV diesel engine to investigate particulate emissions from rapeseed-FAME compared to ULSD and a GTL synthetic diesel fuel.[169] Particle size distributions were measured using a combination of electrical low pressure impactor (ELPI) and SMPS instruments. A clear increase in nucleation mode particles (10-20 nm) was seen with use of biodiesel, along with a decrease in accumulation mode particles (30-300 nm). When treated with a thermal denuder (at 265°C) to drive off volatiles, the biodiesel emissions still contained a higher number of nucleation particles compared to base fuel. The authors speculated that this increase in non-volatile nucleation mode particles could arise from impurities from production of the biodiesel, such as triglycerides or ash-forming metals (Na and K). They also pointed out that these non-volatile particles could be removed by use of a diesel particulate trap.

In summary, under nearly all operating conditions, use of biodiesel reduces the number of accumulation mode particles, and hence, the total PM mass. However, several researchers have observed increases in the number of nucleation mode particles when using biodiesel. There is good evidence that these particles arise from condensation of unburned fuel, or fuel impurities. It is expected that a diesel particulate trap would be highly effective in eliminating these nucleation mode particles.

4.7 Other Non-Criteria Emissions

With conventional diesel fuel, emissions of particulate PAH are of some concern. Several recent reports have appeared in which the PAH emissions from biodiesel and conventional diesel are compared. For example, Lea-Langton and co-workers tested biodiesel produced from yellow grease in a 6-cylinder, HD Perkins diesel engine operated under two steady-state modes.[170] The biodiesel fuel produced lower levels of most PAH, except for fluoranthene and pyrene when operating at low load. The authors suggested that these PAH may be formed through pyrosynthetic mechanisms. Turrico-Baldassarri and co-workers used B20 (rapeseed FAME) in a 6-cylinder, Euro 2 HD bus engine and observed slight reductions in most PAH species measured in both the gas-phase and particle-phase.[130] However, these reductions were generally not statistically significant.

Lin and co-workers tested a range of seven palm-FAME blends over a range of B0 to B30 in a HD diesel engine, and measured numerous PAH compounds in each of nine MOUDI impactor size cuts.[171] They observed that changes in particle size and PAH concentration both occurred with increasing B-level, but followed different trends. The authors concluded that for optimum PAH reduction, biodiesel should be used between B15 and B30.

In a study already mentioned above, Chien and co-workers collected PM emissions in four size ranges and analyzed them for individual PAH species.[165] Biodiesel from yellow grease was blended into conventional diesel at levels of B0, B20, B60, and B100. As B-level increased, PM mass decreased, and PAH level decreased to an even greater degree. The distribution of PAH across the size ranges was found to be similar to the distribution of total PM.

Finally, Karavalakis and co-workers tested soy-based biodiesel in a Euro 2 LD vehicle, using several dynamometer cycles.[172] It was found that under all driving conditions, use of biodiesel resulted in reduced PAH emissions. However, there were several cases where B100 gave higher PAH emissions than B50. Reasons for this were not definitively established, but are thought to relate to combustion differences resulting from use of neat biodiesel. In a subsequent study, this group tested B20-B50 blends (from soy and yellow grease) in a Euro 4 LD vehicle equipped with a diesel particulate filter (DPF).[152] They observed that with the soy-FAME blends, PAH emissions were reduced compared to ULSD base fuel, but with the yellow grease derived FAME, PAH emissions were increased. The authors suggested that some of this increase could be attributed to *de novo* formation of PAH species within the DPF. Increased PAH formation from use of yellow-grease-derived biodiesel was also noted by Ballesteros et al., who used a 2.2L Nissan diesel engine without any after-treatment system.[173] When using rapeseed-FAME, consistent reductions in PAH were measured.

In summary, the available information regarding biodiesel's impact on PAH emissions is quite limited. Nevertheless, it appears that in most cases, use of biodiesel provides a PAH reduction benefit compared to base fuel. The magnitude of these effects is quite small, and likely to be insignificant when using low concentration blends such as B20.

4.8 NOx Effects

Of all the criteria emissions, NOx is perhaps the most controversial and difficult to understand and control. As shown in the sections above, use of biodiesel and biodiesel blends has a strong and consistent beneficial effect on emissions of HC, CO, and PM. However, for NOx, the effects are much smaller and variable. In a recent survey on the emissions effects of biodiesel, Lapuerta et al. stated that about 95% of the relevant literature indicates a reduction in HC and PM from use of biodiesel, 90% indicates a reduction of CO, but only 85% indicates an increase in NOx.[128] Two of the most thorough and best

documented reports of NOx emissions effects from use of biodiesel were issued by EPA in 2002 [174] and by NREL in 2006.[126]

4.8.1 NOx Formation Mechanisms

In diesel exhaust, NOx is predominantly composed of NO, with lesser amounts of NO_2. Under most conditions, other oxides of nitrogen – such as N_2O, N_2O_5, NO_3 – are negligible. NOx formation mechanisms have been studied in some detail, and several literature references give good summaries of this area.[175,176,126,174] In general, three formation processes are believed to be important:

1. Thermal NOx. At high temperatures, such as occur within the combustion chamber of a diesel engine, N_2 and O_2 can react through a series of chemical steps known as the Zeldovich mechanism. NOx formation occurs at temperatures above 1500°C, and the rate of formation increases rapidly with increasing temperature. Under most diesel engine combustion conditions, thermal NOx is believed to be the predominant contributor to total NOx.[177,175,178] The kinetics of the Zeldovich mechanism are such that the timescale of NOx formation is comparable to combustion duration in a diesel engine. [179] Because of this, any effect of biodiesel that increases the residence time of the in-cylinder mixture, or increases the in-cylinder temperature, could lead to increased thermal NOx.

2. Prompt NOx. The formation of "prompt NOx" (also known as "Fenimore NOx") involves reactions of hydrocarbon fragments from fuel combustion – particularly CH and CH_2 – reacting with N_2 in the combustion chamber. [180] The resulting C-N containing intermediates then proceed through reaction pathways involving O_2 to produce NOx. Prompt NOx is only prevalent under fuel rich conditions, where there is an abundance of the hydrocarbon fragments to react with N_2.

3. Fuel NOx. Nitrogen-containing fuel species are oxidized to NOx during the combustion process within a diesel engine. However, since the natural nitrogen levels in both diesel fuel and biodiesel are extremely low, this formation process is negligible.

4.8.2 Theories of Biodiesel's Impacts on NOx

Although use of biodiesel is usually observed to increase NOx emissions, this is not universally true. This is understandable, considering the complexity of the combustion process and the wide range of non-fuel factors that influence emissions – such as air/fuel ratios, engine speed and load, fuel injection timing, and other parameters. The literature contains many reports of experimental studies in which use of biodiesel either reduced NOx emissions, or had no impact. Some of these involve simple, single-cylinder laboratory test engines, with rather unsophisticated controls [181,182,183,184,185], while others involve laboratory engines (and vehicles) more representative of commercial applications [186,187,188,131,126,189]. Several recent studies using modern, highly instrumented test engines and sophisticated diagnostic systems have also demonstrated operating conditions whereby use of biodiesel resulted in reduced NOx emissions.[190,159,191]

Thus, NOx emissions do not show a single, uniform response to the use of biodiesel. Rather, the results vary depending upon numerous factors – including engine type and configuration, duty cycle, fuel injection strategy, emissions control strategy, and other factors. A number of theories have been developed to help understand these factors, and help explain the predominance of test data showing increased NOx with use of biodiesel. Several of the major theories are briefly summarized below:

1. Speed of sound and bulk modulus of compressibility.

   In older style "pump-line-nozzle" (PLN) fuel injection systems, the fluid properties of speed of sound and isentropic bulk modulus have important impacts on the injection process. The isentropic bulk modulus is a measure of a fluid's compressibility under pressure – it affects the amount of pressure rise that will occur from the fuel pump pulse. The speed of sound in the fuel affects the time required for the pressure rise to proceed through the fuel line and reach the injector. Compared to petroleum fuel, biodiesel is less compressible and has a higher speed of sound.[192,193] Both of these factors contribute to an advance in fuel injection timing – by about 1-2° [194,195,196] Injection timing advance can lead to earlier start of combustion, which raises peak in-cylinder temperature, thereby increasing thermal NOx formation. [197] It has also been shown that the speed of sound and isentropic bulk modulus of FAME materials both increase with increasing levels of unsaturation.[192,193] Thus, the injection timing advance – and resulting NOx increase – could be more significant with more highly unsaturated biodiesel (such as soy-FAME) than with highly saturated biodiesel (such as palm-FAME).

   With more advanced "common rail" electronic-controlled injection systems that are typically used today, these fluid properties of speed of sound and bulk modulus of compressibility are no longer very important with respect to the injection process. Careful experimental studies have been conducted with common rail injection systems, and have demonstrated that the inadvertent timing advance when using biodiesel no longer occurs.[198,199] However, even with modern injection systems, the problem of biodiesel's NOx effect remains. Therefore, this theory based upon increased speed of sound and bulk modulus with biodiesel does not provide a complete explanation of the NOx effect.

2. Prompt NOx formation.

   Prompt NOx (or Fenimore NOx) arises via reaction processes involving hydrocarbon fragments. It is thought that due to high levels of unsaturated compounds, combustion of FAME may produce more hydrocarbon radicals than combustion of conventional diesel, thus leading to higher NOx formation.[200] Although there is some modeling support for this theory, there is little experimental evidence for it.

3. Decreased Radiative heat loss.

   It is well known that use of biodiesel reduces PM emissions substantially. Within the combustion chamber, soot particles are effective in radiative heat transfer, thereby lowering the overall flame temperature. Therefore, a reduction in soot concentration would lead to higher combustion chamber temperatures, thereby increasing thermal NOx formation (Zeldovich NOx). There is some experimental evidence from optical engine work to support this theory, [199] and it is consistent with the observation that use of biodiesel generally reduces PM while increasing NOx. Yet, this theory does not provide a complete explanation, as other work has shown that combustion of some FAME species (especially unsaturates) increases both PM and NOx.[158,201]

4. Adiabatic flame temperature.

   It has been shown with combustion of model compounds, that unsaturated molecules exhibit higher adiabatic flame temperature than their saturated counterparts.[200] This has been used to hypothesize that biodiesel gives higher flame temperature than conventional diesel, due to the high concentration of unsaturated compounds in biodiesel. Because of this higher temperature, increased thermal NOx formation would be expected.

5. Other fuel explanations.

    Several other fuel-related theories have been suggested to help explain the biodiesel NOx effect. For example, it has been suggested that the boiling point and volatility of FAME could have an effect on the injection and combustion processes in such a way as to increase NOx emissions.[202,203] FAME materials have much narrower distillation ranges than conventional diesel, and have lower overall volatility. [The biodiesel standard, ASTM D6751, includes a maximum T90 specification of 360°C, as compared to the conventional diesel standard, ASTM D 975, of 338°C.]

    Other researchers have found relationships between FAME density and NOx emissions. [195] With FAME having higher density than conventional diesel, equivalent volume injection results in greater mass injection of biodiesel.

    Theories involving cetane number have also been proposed. Within a range of biodiesel types, NOx emissions have been observed to decrease as cetane number increases. In fact, use of cetane improvers have been explored as a means of mitigating the biodiesel NOx effect.[204] However, due to its typically higher cetane, a shorter ignition delay period would be expected with biodiesel compared to conventional diesel. Ordinarily, this would be expected to reduce NOx – the opposite of the observed biodiesel NOx effect.

6. Other injection/combustion theories.

    In explaining biodiesel's NOx effect, several researchers have investigated ways in which FAME affects the combustion process. In these explanations – which largely overlap with the above-mentioned theories – it is useful to define three separate periods within the overall combustion cycle:

    - Ignition delay period: time between start of injection and start of ignition

    - Pre-mixed combustion period: also called uncontrolled combustion period

    - Diffusion combustion period (also called controlled combustion period)

    The ignition delay period is the time between start of injection and start of ignition. This period is determined by the cetane number of the fuel; with higher cetane leading to shorter ignition delay. A shorter ignition delay could allow the fuel mixture and initial combustion products to have a longer residence time at elevated temperature, thereby increasing thermal NOx formation.

    During the pre-mixed combustion period, fuel and air that have already mixed ignite, causing a rapid rise in temperature and pressure. The extent to which these temperature and pressure increases occur depends upon the amount of fuel that has already been injected, which is related to the length of the ignition delay. With longer ignition delays (related to low cetane number), more fuel is injected and mixed with air before ignition occurs, thus leading to more extreme temperature and pressure increases. Several laboratory studies have shown a relationship between the fraction of biodiesel fuel combusted during the pre-mixed period, and the amount of NOx emissions.[205] Because of biodiesel's oxygen content, it may pre-mix more thoroughly during the ignition delay period than conventional diesel fuel, such that a greater fraction of biodiesel burns during this period, resulting in larger heat release and increased thermal NOx formation.

    During the diffusion combustion period, fuel is continuing to be injected into the cylinder, and combustion occurs in regions where sufficient air has diffused into the flame region to provide the proper air/fuel ratio. Under some operating conditions, diffusion flame temperature is believed to be the dominant factor in determining NOx formation.[199]

7. Engine control/calibration theories.

Modern diesel engines are equipped with electronic engine control modules (ECMs) that are programmed to control air/fuel ratios, injection timing, EGR, and other important parameters. The control strategy typically employs measurements of engine speed and torque, which are used to define operating conditions that maximize fuel economy while satisfying emissions requirements. Programming of the ECM control settings is generally based upon use of conventional diesel fuel. If use of biodiesel causes perceived changes in speed or torque, the ECM would make adjustments to operating conditions which could result in higher emissions.

A recent paper by Eckerle et al. provides a thorough discussion of how NOx increases can occur because of such ECM-related modifications.[206] Due to biodiesel's lower volumetric energy content, a higher fuel flow is required compared to conventional diesel. The ECM interprets this higher fuel flow as an indicator of higher torque, and therefore makes adjustments to engine operating parameters that increase NOx emissions.

Eckerle et al. also explain that the total biodiesel NOx effect is determined by the sum of two different influences: (1) engine control effects (as described above) and (2) fundamental combustion effects. The fundamental combustion effects are driven by fuel chemistry and fluid dynamics, and are applicable to all engines; while the engine control effects are specific to the particular engine calibration being employed, and likely differ from one engine type to another. The relative contributions of these two effects vary depending upon the specific fuel and engine load. For example, under high load conditions, a diffusion flame combustion process dominates, and engine controls have a more significant influence on biodiesel's NOx increase. Under low load conditions, with more pre-mixed combustion, the fundamental combustion effects can be more influential than the engine control effects.

A recent report by Jacobs et al. supports this theory of increased NOx from biodiesel usage in a modern, ECM-equipped diesel engine.[207] Jacobs found an average NOx increase of 20% over nine operating points when using palm-FAME compared to conventional diesel. However, it was noted that when using biodiesel, the ECM adjusted several parameters (boost pressure, EGR level, and start of combustion) to attain the same torque. The authors suggested that these ECM-directed changes could be partly responsible for the increased NOx that was observed.

Several laboratories have conducted sophisticated experiments involving modification and control of injection and combustion processes in an attempt to test various theories used to explain the NOx effects of biodiesel. Cheng at al. used an optically-accessible engine to permit clearer observation of these processes.[199] They also modified engine and fuel conditions to maintain a constant start of combustion (SOC) and premixed burn fraction; yet biodiesel was found to give higher NOx emissions than conventional diesel. Experimental measurements indicated that combustion flame temperatures were higher with biodiesel. This was explained by differences in soot radiative heat transfer; with biodiesel producing less soot, thus having higher in-cylinder temperatures.

In subsequent work with the same optical engine, constant start if injection (SOI) and start of combustion (SOC) were maintained, chemical additives were used to increase radiative heat transfer, and diluted intake air was used to simulate EGR. [179] Several different biodiesel blends were used, and the engine was operated over a range of loads. A major conclusion from this study is that no single mechanism or fuel property can explain the biodiesel NOx effect under all conditions, but rather, several mechanisms are important. These different mechanisms can either reinforce or cancel one another, depending upon specific operating conditions. Two factors identified as being most important are: (1) combustion phasing – earlier start of combustion with biodiesel, leading to longer residence times and higher temperatures,

and (2) lower radiative heat loss with biodiesel. These authors also concluded that the controlling mechanisms leading to higher NOx from biodiesel were different between low and high engine load conditions.

Adi and co-workers used a modern, ECM-equipped heavy-duty engine to explore various theories of the biodiesel NOx effect.[208] They compared the performance of soy-FAME with conventional diesel under three different speed-torque conditions, all of which are dominated by diffusion flame combustion. Substantial NOx increases with biodiesel were found at all three operating points. These data were then combined with other information to drive a computational engine combustion model to investigate the impacts of biodiesel upon NOx. This combination of experimental and modeling work showed that biodiesel can increase NOx emissions due to high in-cylinder temperatures under both pre-mixed and diffusion combustion conditions. During the pre-mixed stage, the higher oxygen levels with biodiesel (due to the fuel oxygen) produce conditions closer to stoichiometric, which results in higher in-cylinder temperatures. During diffusion combustion, greater availability of oxygen with biodiesel leads to higher flame temperature. An additional factor with EGR-equipped engines is that EGR gases from biodiesel combustion contain higher O_2 levels than gases from conventional diesel combustion. Consequently, use of EGR with biodiesel is less effective in reducing in-cylinder temperatures; or alternatively, a greater degree of EGR is necessary when using biodiesel fuel.

In another carefully controlled laboratory study, Schonborn et al. conducted a series of experiments in which they controlled three important parameters: (1) injection timing, (2) ignition timing, and (3) ignition delay.[158,201] Individual FAME species were used, rather than complete biodiesel fuels. Results showed that all three of these parameters are important, but to different degrees with different FAME structures. These researchers also demonstrated the important role of unsaturation in determining NOx emissions, with higher unsaturation leading to higher NOx. It was concluded that the formation of NOx is controlled by several, layered effects, with the most important being ignition delay, which changes heat release behavior and stoichiometry of the combustion process. Adiabatic flame temperature is regarded as a secondary effect, which only becomes important when the effect of ignition delay is removed. Soot-influenced radiative heat transfer is regarded as a tertiary effect.

Jacobs and co-workers used a modern medium-duty test engine to investigate differences in the response of an electronically-controlled, common rail injection system when using biodiesel and conventional diesel fuels.[209] They confirmed that the unintended advance in injection timing with biodiesel in pump-line-nozzle systems does not occur with modern common rail systems. They also demonstrated that the injection pulse width is longer with biodiesel, since more fuel must be injected to compensate for its lower volumetric energy content. From heat release measurements it was shown that biodiesel had a shorter ignition delay (earlier start of combustion), earlier start of diffusion burning, and earlier termination of combustion. Consistent with the observations of Mueller at al., [179] biodiesel appears to promote a combustion process that is shorter and more advanced than conventional diesel. These changes would be expected to increase thermal NOx emissions.

Yoon and coworkers investigated differences in fuel injection spray behavior between biodiesel and conventional diesel.[210] They observed that biodiesel gave larger droplet sizes, narrower spray patterns, and longer spray tip penetration into the combustion chamber. Others have used computational fluid modeling to show that narrower, but longer spray penetration would be expected to increase NOx, due to higher average cylinder gas temperatures.[211]

4.8.3   Effects of Fuel Properties

Despite the small and variable effects of biodiesel on NOx emissions, a strong consensus has developed throughout the literature regarding certain fuel properties that are responsible for these effects. As early as

2003, an NREL report identified FAME unsaturation and chain length as two key properties affecting NOx emissions.[129] It is generally accepted that NOx emissions increase with increasing unsaturation, but decrease with increasing chain length. These effects have been noted in several reviews of biodiesel emissions effects [68,204] and have been demonstrated experimentally in numerous studies involving pure FAME constituents, [212,213,158] as well as complete biodiesel fuels in single cylinder test engines, [214,215] light-duty engines, [216] and heavy-duty engines.[213,217,218]

The exact mechanisms responsible for these fuel compositional effects on NOx are still somewhat controversial, and largely follow theories similar to those discussed above in Section 4.5.2. For example, higher unsaturation correlates with higher adiabatic flame temperature, which influences thermal NOx formation. Also, higher unsaturation is related to lower cetane number, which affects ignition delay and changes phasing between pre-mixed and diffusion flame combustion processes. Iodine value (IV) is a good surrogate for unsaturation, and several researchers have noted the strong relationship between IV and NOx emissions.[219,187,220,213] Differences in NOx emissions by biodiesel type have also been noted in the literature, with more highly unsaturated feedstocks (such as soy) producing higher NOx than less saturated feedstocks (such as rapeseed, tallow, and yellow grease).[174,204,189]

With the magnitude of the NOx effects generally being much less than the CO, HC, and PM effects, it is often difficult to quantify – or even confidently detect – a NOx effect when using low concentration biodiesel blends, such as B20 or below. In a recent publication, Yanowitz and McCormick concluded that the NOx emissions arising from B0 and B20 test fuels across a large number of test cycles and engines were not statistically significantly different.[125]

There is also some evidence that the composition of the base diesel fuel into which the biodiesel is blended has an impact on the NOx emissions. In EPA's 2002 review, it was observed that larger NOx increases occurred when biodiesel was blended into "clean" base fuels as compared to "average" base fuels. [174] ("Clean" base fuels generally had lower aromatics, higher cetane number, lower density, and lower distillation temperatures as compared to "average" base fuels.) To address this concern of larger NOx increases in clean base fuels (such as CARB diesel fuel), the California Air Resources Board is currently conducting an experimental program to quantify the NOx effects in CARB diesel, and to identify effective mitigation measures.[204,221]

In the 2003 NREL report, both biodiesel methyl esters (FAME) and ethyl esters (FAEE) were tested in a 1991 DDC HD engine.[129] Differences in NOx emissions between the FAME and FAEE fuels were variable and inconclusive. The authors concluded that neat FAME and FAEE originating from the same base stock produced the same NOx emissions. More recently, using a LD diesel engine with common rail injection, Lapuerta et al. determined that FAEE (from used cooking oil) gave slightly reduced NOx compared to FAME.[222] This effect was attributed to either FAEE's slightly higher cetane number, or its slightly lower oxygen content. Using pure compounds in a single-cylinder test engine, Schonborn et al. also observed a slight decrease in NOx emissions with FAEE as compared to FAME.[201,158]

4.8.4   Effects of Engine Load

In their 2006 report, McCormick et al. noted that the impacts of biodiesel blends (B20) upon NOx emissions were highly dependent upon the test vehicle/engine and the driving cycle being used.[126] Subsequently, using a common rail LD diesel engine, Zhang and Boehman demonstrated that biodiesel blends could increase NOx emissions under high load operating conditions, but decrease NOx under low load conditions.[198] More recently, Karavalakis et al. noted that NOx increases with biodiesel usage in LD vehicles occurred under some test cycles, but not under others. [153] Also in a modern LD application, Zhang and coworkers showed that the NOx increase with use of biodiesel blends is a function of engine load.[223]

In the Cummins study already described above, a combination of experimental work and modeling showed that NOx effects of biodiesel in a HD engine vary significantly with load.[206] Under high loads, specific engine calibration strategies that are employed can increase NOx significantly; while under low loads, biodiesel use could have no effect on NOx -- or even decrease NOx emissions.

Using a single HD diesel engine (2006 Cummins ISB) on a dynamometer, EPA investigated the NOx effects of several biodiesel blends when tested over 7 different engine cycles.[224] The results showed that NOx emissions increased as a function of average cycle load – using both engine cycles and chassis-based cycles. In their RFS2 Regulatory Impact Analysis, EPA included retrospective analysis of other literature-reported NOx effects, and concluded that they could be understood by analyzing the emissions results as a function of cycle load.[9] Due to this identification of cycle load as being an important determinant of NOx effects, the current CARB study is now investigating the impacts of test load when using biodiesel blends in CARB diesel.[204,221]

4.8.5   Effects of Fuel Temperature

Low temperature operation of biodiesel is a significant concern with respect to wax formation, fuel gelling, and the impacts on filter plugging and general engine operation. A few researchers have also investigated the effects of temperature on NOx emissions. Using a mechanically activated fuel injection system, Kegl showed that NOx emissions increased as fuel temperature decreased.[66] This was attributed to an earlier start of injection, but longer ignition delay at lower temperatures. Kegl also observed that at low temperature, the distribution of biodiesel fuel among the 6 injectors comprising the entire fueling system became quite uneven, due to increased fuel viscosity. This uneven fuel distribution would also be expected to adversely affect exhaust emissions.

Mamat et al. investigated the effect of biodiesel fuel temperature upon engine operation and emissions from a common rail LD diesel engine.[225] The objective was not to explore low temperature operability, but to investigate the impacts of increasing fuel temperature above ambient. It was shown that by increasing the fuel temperature from 30°C to 40°C, NOx emissions from biodiesel could be reduced – in the absence of EGR. Application of EGR reduced NOx overall, but the benefit of fuel temperature increase no longer occurred.

Finally, Bannister et al. conducted a temperature-controlled chassis dynamometer study using a Euro 3, common rail, LD vehicle.[226] Ambient temperature was controlled from 25°C down to -5°C, and biodiesel blend ratios were explored from B0 to B50. The usual increase in NOx emissions with increasing B-level was observed, but the magnitude of this increase diminished at lower temperatures.

4.8.6   Mitigation of NOx Increases

While use of biodiesel generally provides emissions benefits with respect to CO, HC, and PM, the slight NOx increase usually observed is regarded by some as a problem requiring mitigation. Numerous different mitigation approaches have been explored by many different investigators. However, these approaches can be broadly categorized into two groups: (1) engine modifications and (2) fuel modifications. Examples of both categories are provided below.

4.8.6.1 Engine Modifications

In their 1998 review paper, Graboski and McCormick noted that use of biodiesel increased NOx emissions in both 2-stroke and 4-stroke diesel engines, but that these increases could be effectively mitigated by retarding the fuel injection timing by 1-4°.[227] Subsequently, Choi and Reitz demonstrated

the NOx reduction benefits of injection retard and split injection techniques when using biodiesel in a HD Caterpillar engine.[228] The authors argued that these injection strategies reduced the amount of pre-mixed burning, thereby reducing in-cylinder temperatures. The NOx reduction benefits of split injection techniques were further confirmed by Kim et al. using a single-cylinder test engine with a common rail injection system, [229] and by Stringer et al. using an optical access laboratory engine.[230] Using a 6-cylinder MAN bus engine, Kegl demonstrated that biodiesel could actually produce lower NOx than conventional diesel fuel, if the injection timing were retarded to achieve maximum torque.[231]

A second engine modification to reduce NOx emissions is use of EGR. The major effect of EGR is reduced cylinder temperature, due to introduction of diluent gas of high specific heat (containing substantial levels of H_2O and CO_2). Additionally, introduction of EGR reduces the oxygen content in the cylinder. Both of these factors are believed to contribute to reduced NOx emissions.[232] Several other investigators have reported on the benefits of EGR in reducing NOx emissions when using biodiesel in laboratory test engines.[233,234,235,236] EGR is also commonly used to reduce NOx emissions when using conventional diesel fuel. Thus, to be effective in a biodiesel situation, a greater degree of EGR would be utilized. The use of EGR in combination with a diesel particulate filter (DPF) is an effective way to reduce both NOx and PM from diesel engine exhaust.[237]

More effective than either injection timing or EGR alone is the combination of both approaches, utilizing a control system to maximize the overall benefit.[175] Several investigators have demonstrated such enhanced benefits when using biodiesel in single-cylinder laboratory engines, [232,238,239] and multi-cylinder engines.[198,240,241,159,242] Of course, effective use of such engine strategies requires on-line analysis of the fuel composition, and an ability to adjust parameters depending upon this composition.

In recent years, several investigators have explored a type of combustion process known as low temperature combustion (LTC). Good descriptions of LTC can be found in the literature.[243,244,245] In general, LTC involves use of high EGR rates (up to 50%), high injection pressures, multiple fuel injection pulses per cycle, and late main injection (even after TDC). With LTC, ignition delay increases, thus increasing the pre-mixed combustion phase and decreasing (or eliminating) the diffusion flame combustion phase. The overall in-cylinder temperature is reduced substantially, thereby reducing NOx formation. At the same time, PM is reduced due to the dominance of lean, pre-mixed combustion. In some respects, LTC resembles homogeneous charge compression ignition (HCCI) combustion; and some researchers consider HCCI to be a subset of LTC.[245,246,247,248]

LTC is not appropriate for all operating conditions, and it is known to increase CO and HC emissions in some situations. Yet, it appears to be a very attractive strategy since it offers simultaneous and significant reductions of both NOx and PM. Numerous laboratory applications of LTC have been published in recent years, with positive results reported from modeling studies, [249,230] single-cylinder test engines, [246,245,247,250,251] and multi-cylinder production engines.[243,252,244,253,254]

4.8.6.2 Fuel Modifications

Changes in fuel composition have long been suggested as ways to mitigate the NOx increase resulting from use of biodiesel (and biodiesel blends), while still benefitting from the reductions in HC, CO, and PM that such fuels offer. In 1996, Graboski et al. tested a variety of biodiesel blends in a 1991 DDC Series 60 engine, using the EPA HD transient test protocol.[255] The emissions results were used to extend the fuel effects model developed under CRC Project VE-1. From this, the authors concluded that the NOx increase from B20 usage could be eliminated by reducing the base fuel's aromatic content (from 34.3% to 29.7%) or by increasing the cetane number (from 46.2 to 52.8). These model-predicted emissions changes were not experimentally confirmed at this time.

Some years later, this same DDC Series 60 engine was used in an experimental program to investigate NOx mitigation when using B20 blends from soy oil and yellow grease.[256] Three different hydrocarbon base fuels were used to make the B20 blends: (1) federal certification fuel (31.9% aromatics; 0.04% sulfur), (2) 10% low aromatics diesel (7.5% aromatics; 0.01% sulfur), and (3) F-T diesel (0% aromatics; <0.01% sulfur). Based upon results of HD FTP testing, it was demonstrated that NOx emissions from B20 blends were reduced considerably when using either the 10% low aromatics diesel or the F-T diesel in place of the conventional diesel fuel. Using linear extrapolation of the results, the authors concluded that a base fuel having 25.8% aromatics would provide a "NOx neutral" B20 blend relative to use of the certification base fuel (at 31.9% aromatics). When using the F-T diesel as base fuel, a biodiesel blend as high as B55 was predicted to be NOx neutral. Also in this study, the effects of cetane improvers upon NOx were determined. Both di-t-butyl peroxide (DTBP) and 2-ethylhexyl nitrate (2-EHN) were shown to be effective. The authors concluded that "perhaps the most practical strategy for NOx reduction in the short term is the use of cetane improvers."

In a related study McCormick et al. again demonstrated the effectiveness of cetane improvers, DTBP and 2-EHN, in reducing NOx emissions from biodiesel blends.[189] They also observed a NOx reduction with use of the anti-oxidant additive, t-butyl-hydroquinone (TBHQ). Although both the cetane improvers and anti-oxidants were somewhat effective, no additive combination in B20 blends based on federal certification diesel fuel could match the NOx reductions provided by a CARB low aromatics (nominally 10% aromatics) diesel fuel. However, reducing the certification diesel fuel's aromatics content from 32% to 25%, combined with use of DTBP, did meet the CARB fuel's performance. The authors also reported that B20 NOx emissions were higher with soy-derived FAME than with yellow grease-derived FAME. They attributed this to the higher unsaturation of the soy material, which had an iodine value of 127, compared to 79 for the yellow grease.

Several other groups have reported on the beneficial effects of cetane improvers in reducing NOx emissions from biodiesel and biodiesel blends, with ETBP and 2-EHN being the two most frequently employed additives. Positive effects have been found in single cylinder laboratory test engines [257,258] as well as production HD engines [259,260,261,204], although the effectiveness varied depending upon specific engine and operating conditions. In some cases, DTBP has been found to be more effective than 2-EHN. [204,260] Also, Yanowitz and McCormick, who recently reviewed the literature regarding fuel effects of biodiesel in HD engines, concluded that the effectiveness of cetane improvers appears to diminish with newer engine technologies, that already meet lower NOx emission requirements.[125]

Another common fuel modification for reducing NOx emissions from biodiesel involves blending with other materials that are inherently low NOx emitting, especially F-T fuels.[204,256,262] However, other blending strategies have also been reported, including blending biodiesel with renewable diesel, [204,221] blending soy FAME with pure methyl oleate (18:1) [257], use of partially hydrogenated soy FAME, [178] use of soy polyols, [263] and use of water/biodiesel emulsions.[264]

4.8.7 Impacts on Exhaust After-Treatment Systems

With NOx emissions standards becoming increasingly stringent (see Table XVIII), exhaust after-treatment systems are now being introduced to meet the NOx requirements in both LD and HD applications. Because standards requiring use of after-treatment are quite recent, there is little operational experience with such systems reported in the literature.

Two types of after-treatment approaches are commonly employed to reduce NOx emissions from diesel engines. One involves use of a NOx adsorber catalyst (NAC), which is sometimes called a lean-NOx trap. A NAC system utilizes an oxidation catalyst to convert all NO to NO_2, which is then trapped in an adsorbent bed. Once the adsorber is saturated with NO_2, the exhaust stream is forced into a fuel-rich

condition (by injection of excess diesel fuel, or other means) and the trapped NO_2 is reduced to N_2, which is exhausted. NAC systems are very sensitive to sulfur contamination, since SOx is collected in the adsorbent bed along with NOx. However, the lean operation mode used to remove NOx is not effective in removing SOx, thus sulfur contamination gradually reduces the trapping capacity for NOx.

The second NOx after-treatment approach is called selective catalytic reduction (SCR). With SCR, a different catalyst bed is used to directly reduce NOx to N_2. However, this requires separate injection of a chemical reductant into the exhaust stream, ahead of the SCR catalyst. The most commonly used reductant is ammonia, typically used in the form of an aqueous urea solution. (Urea readily reacts in hot exhaust to produce ammonia.) A slight excess of ammonia is helpful in maximizing reduction of NOx in the SCR catalyst, but this results in "ammonia slip" emissions. An additional oxidation catalyst may be used to treat this ammonia slip.

Both NAC and SCR are generally used as components within more extensive after-treatment systems that also include components such as PM traps, oxidation catalysts, O_2 sensors, and other devices. Optimized performance of a complete aftertreatment system requires sophisticated monitoring and control systems. Engine and vehicle manufacturers employ various proprietary strategies to integrate the multiple components within a complete after-treatment system, and control their operation and performance. Other engine parameters, such as EGR and injection phasing, are also included as part of the entire emissions control system. Because of the variations in control strategies, and variations in the performance of after-treatment systems under different operating conditions, it is not likely that use of biodiesel will provide a consistent NOx effect in all situations.

To better understand the NOx impacts of biodiesel in modern engines using sophisticated after-treatment systems, a few research groups have performed controlled laboratory experiments. One research team, consisting of NREL and FEV, Inc., has reported testing of biodiesel in a light-duty Tier 2 diesel engine and vehicle.[265,266] ULSD base fuel was used, with biodiesel blends of B5 and B20 (soy-based FAME). Three common chassis dynamometer test cycles were investigated: FTP-75, US06, and HFET. Two different after-treatment systems were independently tested: (1) NAC followed by a catalyzed diesel particulate filter (CDPF) and (2) SCR followed by a DPF.

From testing of the NAC system it was shown that engine-out NOx was somewhat higher when using B20 compared to B0 (by up to 10%), while tailpipe-out NOx was slightly lower when using B20. This was attributed to higher exhaust temperatures with B0 compared to B20 – resulting from calibration of the engine/aftertreatment system with B20 rather than with B0. As a consequence of this higher exhaust temperature, the NAC was less effective in trapping NOx when operating on B0. Engine dynamometer testing of the NAC system showed no impact of B20 with respect to timing or actuator settings for controlling lean-rich modulation. With the SCR system, no difference in tailpipe-out NOx was observed. Overall, the impacts of B20 on the performance of both emission control systems were negligible to slightly positive (with NAC). Furthermore, B20 use was not found to affect the durability of these emissions control systems.

In a different laboratory study using a 4-cylinder, 4.0L diesel engine (from Hino Motors) equipped with a NAC, Kawano et al. reported that use of 100% biodiesel (rapeseed-FAME) under steady-state operating conditions resulted in much higher NOx compared to use of conventional diesel fuel.[236,267] This was attributed to insufficient desorption of NOx from the trap during the fuel-rich spike conditions used for trap desorption. Two reasons for this poor performance were suggested: (1) because of it high oxygen content, biodiesel is inherently leaner than conventional diesel; thus requiring a larger fuel spike volume to achieve the rich conditions necessary to desorb the NOx trap, and (2) biodiesel has higher density and viscosity than conventional diesel, adversely affecting the atomization and volatilization of the fuel when spiked into the exhaust system.

Yoshida et al. tested B30 (rapeseed-FAME) in a modern Toyota LD passenger car equipped with a diesel particulate and NOx reduction (DPNR) emission control system, which includes a NAC.[268] Compared to the ULSD base fuel, use of B30 was shown to reduce CO, HC, and PM, but have no effect on NOx. Using the same vehicle type, Lance et al. explored a range of biodiesel blends from B5 to B100, with the fuels produced from several different feedstocks.[269] The New European Drive Cycle (NEDC) was utilized, and numerous emissions species were measured. From blends of B30 and below, minimal NOx increases were observed, while larger increases occurred when using B100.

Very recently, Williams et al. described a laboratory study to investigate how use of biodiesel affects the performance of a Fe-zeolite SCR catalyst used for NOx reduction.[270] These catalysts are meant to adsorb NOx during normal operation, and then release the NOx (as N_2) during a fuel rich spike. However, they also adsorb hydrocarbons during low temperature conditions, thereby inhibiting the catalyst's NOx reduction ability until the temperature is increased and the hydrocarbons are desorbed. These researchers used a combination of laboratory flow reactor and engine tests with ULSD and B100 fuels. It was demonstrated that B100 exhibited the same catalyst masking behavior as did ULSD, but the recovery time was faster with B100. Using ULSD, NOx conversion was inhibited until the catalyst reached a temperature of 400°C, while only 200°C was needed with B100.

In summary, based upon the information currently available, it appears that use of biodiesel – especially at blend levels of B20 and below – does not seriously affect the performance of either NAC-based or SCR-based after-treatment systems. However, as both of these technologies have been in commercial use for only a short time, further long-term study is warranted.

5.   CARBON FOOTPRINT OF BIODIESEL AND RENEWABLE DIESEL

5.1   Introduction and Background

Numerous countries have been working to implement alternative fuel policies to increase their portfolio of renewable fuel use. These policies include California's Low Carbon Fuel Standard (LCFS), the EPA's Renewable Fuel Standard (RFS2), the EU's Renewable Energy Directive (RED), and the UK's Renewable Transport Fuel Obligation (RTFO), among others [271,10,9,272]. One of the priorities of these policies is to ensure that greenhouse gas (GHG) reductions will be met through the use of these fuels. Life cycle assessments (LCAs) provide a method to calculate the well-to-wheels GHG emissions (among other environmental impacts) of a fuel. Results from various fuels and scenarios can be compared to a reference fuel such as petroleum diesel to determine the extent of the GHG reductions.

Because of their important role in policy and GHG reduction measures, LCA studies have been under critical review, with each assumption, definition, data input, etc., being evaluated by all stakeholders and experts in an effort to ensure that the life-cycle GHGs or energy use are a representative measure of producing and using a biofuel. Due to growing debates and controversy associated with LCA of biofuels, this area of literature is growing rapidly as entities strive to reach consensus on the methodologies and approaches that should be used.

In previous work (CRC-AVFL-17) the authors conducted a literature survey of LCA of bio-distillates (including biodiesel and renewable diesel). The focus of that survey was to compare and contrast both life-cycle energy and GHG results from different studies, and to highlight assumptions that had the largest influence on results. This previous work illustrated how critical assumptions such as co-product allocation and N_2O conversion ratio influence the final results for both GHG and energy return. Results showed that nearly all biofuels gave a net energy benefit as compared to conventional fuels – meaning that the biofuels contained more energy than was consumed during the life-cycle processes of producing the

biofuel. In nearly all cases, regardless of pathway or feedstock, the results showed that biodiesel and renewable diesel life cycles use significantly less fossil energy than petroleum diesel's life-cycle.

Uncertainties surrounding estimation of GHG have been a concern as policy analysts and stakeholders try to ensure that LCA analysis accurately reflects emissions, so that GHG reduction targets will be met in a sustainable way. In particular, concerns about indirect land use change (ILUC) and how it should (or should not) be included in the analysis is at the forefront of the discussions. Since LCA is being relied upon so critically to support future alternative fuel policies, the previous review has been updated, focusing on LCA studies that are specifically related to GHG calculation, or carbon intensity (CI), and those that focus on land use change (LUC) issues.

5.2 LCA Model Approaches and Assumptions

LCA models and methodologies provide a tool to estimate the complete environmental impacts arising through each stage of a product's life, from manufacturing through disposal. LCA is becoming increasingly common in policies to evaluate alternative fuels' GHG emissions to ensure that GHG reduction targets will be met relative to a reference petroleum fuel. Table XXII shows the targets required for biodiesel and baseline petroleum diesel carbon intensity (CI) for several policies in the U.S. and Europe.

The CI is determined by evaluating GHG emissions produced at all stages from well-to-wheels (WTW), including feedstock growth, harvesting, fuel production, distribution, and combustion, as well as all intermediate transportation and storage steps. The GHG emissions typically include CO_2, CH_4, and N_2O, which are converted into a CO_2 equivalent value ($CO_{2,eq}$). The conversion factors most frequently used are IPCC's 100 year global warming potential (GWP) factors where CO_2=1, CH_4= 26 and N_2O= 296.[273] The total mass of $CO_{2,eq}$ produced is then normalized by the energy contained within the final unit of fuel (g $CO_{2,eq}$/MJ_{fuel}), the unit mass of fuel (g $CO_{2,eq}$/kg_{fuel}), or some other unit.

Table XXII. GHG Reduction Target and Reference Petroleum Diesel CI for U.S. and E.U. Policies

Policy	Petroleum Diesel Reference CI (g $CO_{2,eq}$/MJ_{fuel})	GHG Reduction Target	Biodiesel Threshold CI (g $CO_{2,eq}$/MJ_{fuel})
EPA - RFS2	91.79 (2005 baseline)	50%	45.90
CARB - LCFS	94.71	10%	85.24
EU- RED	83.8	35%	54.47
UK- RTFO	86.4	40% recommended	51.84

To accurately estimate a CI, extensive data is required on all inputs, products, and emissions from each life-cycle state. Numerous modeling tools and databases have been constructed to support fuel LCA. Some of the models used include BEES, BESS, EBAMM, EcoIndicator, EIO-LCA, LEM, GaBi, GHGenius, GREET, GEMIS, and SimaPro. Commonly used databases include NREL's US LCI Database and EcoInvent. The GREET model, developed by Argonne National Laboratory, offers over 200 specific pathways for alternative fuels and vehicles. It is among the most prevalent model in the U.S. and is used by the EPA for the Renewable Fuel Standard (RFS2) [9]. In addition, California has updated the GREET model with its state and regionally specific data to produce the California-GREET model, which the California Air Resources Board (CARB) is using in support of its Low Carbon Fuel Standard (LCFS) [10]. Similar models have been used in support of other policies: GHGenius is used in support of Canadian policy, and SimaPro is used for many European studies. Not all models produce similar results:

EcoIndicator models the LCA of numerous environmental impacts such as those from eutrophication, human toxicity, and others, and aggregates the impact into a single score.

LCA methodologies can be divided into two general categories: Attributional (ALCA), and Consequential (CLCA). In an ALCA, only GHG (or other environmental impacts) that are directly linked to the product lifecycle are accounted for. CLCA estimates GHG emissions that are linked either directly or indirectly to a product, through changes in supply and demand. CLCA are more complex, drawing more expansive boundaries, and may require additional models and assumptions.

Even when models implement similar data or databases, they are likely to produce differing results because numerous assumptions differ from model to model (or modeler to modeler). Some of the key assumptions affecting the results include the following:

- definition of the boundaries
- scale of production
- farming energy and chemical requirements
- amount of nitrogen fertilizer for plant growth
- conversion of nitrogen fertilizer to N_2O
- crop yields
- energy use and efficiencies from biofuel processing plants
- credits given to co-products
- land use change impacts

While some of these assumptions are simply minor variations in practices and methodologies, others can generate significant differences in the final results. Three of the most influential assumptions are described below in more detail.

5.2.1 Land Use Change Impacts

Increasing biofuel production to meet policy targets will likely require additional lands to grow and produce the feedstocks, resulting in both direct and/or indirect land use change (DLUC and ILUC). DLUC occurs if LUC can be attributed to the production of the biofuel itself, e.g., expansion of new cropland occurs to produce the feedstock directly. ILUC results if an existing crop is diverted to biofuel production, triggering a market response that leads to cropland expansion elsewhere.

The effects of land use change (LUC) and how it is considered (or not considered) in LCA and policy has drawn considerable attention. In particular, the area of ILUC has been the focus of much debate since there is considerable potential for significant emissions from the loss of carbon in vegetation (i.e., forests or grasslands) or soils, as well as the loss of on-going carbon sequestration that would have occurred had the land remained in its original state [274]. Many agree that ILUC will likely have some impact, and should be given a non-zero value [275,276,277,9]. However, some argue that current practices for modeling ILUC result in an unacceptable range of uncertainty, so ILUC should not be included until the data are more scientifically robust. [275,278]. Others argue that including ILUC unfairly singles out biofuels, making producers responsible for activities outside of their control. [277,279]

LCA models that include ILUC are complex, requiring inputs from economic models that generate feedback loops to reflect how changes in supply and demand affect price elasticity and co-product markets, and generally require CLCA modeling.[280] These models produce high levels of uncertainty in the results, including concerns about overlapping boundaries and double-counting of emissions. In addition, the following assumptions also add considerable uncertainty:

- Location where the LUC occurs: expansion of croplands into tropical rainforests can have considerably higher effects than expansion into degraded lands.

- Amount of land affected: a displaced crop may be replaced simply through intensification of another cropland, or by creating new croplands. The increase in demand for crops may not create a linear response for cropland, so some assumptions must be made with regard to how increased crop demands are met.

- Soil and vegetation characteristics of the affected land(s): the amount of carbon that is stored can differ significantly from different types of soils or vegetation.

- Time period that the lands remain in production: a large initial release of CO_2 from soil and vegetation occurs as plants are removed and soil is disturbed. Allocation of this intense "burst" of emissions over a short period of time gives different results than allocation over a longer period of time.

Despite the high uncertainties surrounding ILUC, policies that utilize LCA are beginning to incorporate ILUC effects in their modeling approach to determine net GHG benefits of the alternative fuel: California was the first to require ILUC effects in its LCFS [281]; the U.S. EPA is beginning to consider ILUC effects [282]; and the European Commission (EC) is also evaluating the best practices and methods to include ILUC in its policies [272].

The interaction between supply and demand changes of crops is complex to model and requires linking multiple models. For example, CARB has linked its CaGREET model with the GTAP economic model. [283] EPA utilizes a large set of linked modeling tools including the following:

- **GREET**—used as the basic LCA platform to quantify emission factors associated with different life-cycle stages of various fuels.

- **FASOM**— to model the domestic forest and agricultural impacts.

- **FAPRI**—to estimate impacts on international agriculture and livestock production.

- **Winrock International Data Analysis**—utilizes 2001-2004 satellite imagery to analyze recent LUC changes around the world and estimate what types of lands will be converted to crop land in each country.

- **GTAP**—used only to test the robustness of FASOM, FAPRI and Winrock results.

- **DAYCENT/ CENTURY models**—to simulate plant-soil systems, daily soil water and temperature dynamics, trace gas fluxes (CH_4, N_2O, NOx) and to simulate plant production, soil carbon dynamics, soil nutrient dynamics and soil water and temperature.

- **ASPEN**—to supplement GREET to estimate GHG emissions associated with renewable fuel production improvements in technology and process technology.

- **MOVES**—to estimate vehicle tailpipe and GHG emissions for on-road and non-road mobile sources.

- **NEMS** – (EPA version of the Energy Information Administration's National Energy Modeling System) to estimate secondary impacts on the energy market associate with increased renewable fuel production.

ILUC is dealt with in a similar fashion to amortization of capital in economic evaluations. As virgin lands are modified into crop lands, there is a large initial release of CO_2 as a result of vegetation being burned or left to decay, and from carbon already in the soil. This large release of CO_2 must be discounted and amortized over all the units of biofuel that are produced within a specified time period. This requires

defining a time period and a discount rate. The time period, or time horizon, defines the length of time (usually 30 to 100 years) over which the ILUC emissions will be attributed to the fuel. EPA and CARB have both settled on using a 30-year time horizon with a 0% discount rate. The 0% discount rate implies that all future emissions have the same value as today's emissions – i.e. they are neither more nor less important in the future. Additionally, Keeney and Hertel have shown that ILUC depends heavily on yield elasticity, acreage response elasticity, and bilateral trade elasticity in their GTAP model for U.S. ethanol policy. [284]

DLUC may also lead to significant impacts on the final product. DLUC impacts are those that are associated directly with the cultivation of feedstocks used to produce a biofuel in the region where it is used. This includes modification to soil carbon and variations in above ground biomass from preparation of existing crop-lands (including fertilization during cultivation) or conversion to new crop-land.[285] Most LCA models include some type of DLUC assessment to address changes in GHG emissions resulting from modifications to soil carbon. LCA models which only include direct effects have been defined as attributional LCA (ALCA).[286,280]. Methods of including DLUC are also somewhat controversial, specifically with respect to biologically-produced N_2O emissions, which are discussed in more detail below.[287]

Because of the controversial nature of ILUC, special attention is made in this report to results of LCA studies that include an assessment of ILUC.

5.2.2 Nitrogen Fertilizer and N_2O Conversion Ratios

A single gram of N_2O equates to approximately 296 grams of CO_2 in global warming potential, so small changes in N_2O can result in significant differences in CI.[273] 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.[288] Variations in assumptions about N_2O can swing the final CI results of a particular biofuel scenario from positive to negative, compared to a conventional baseline fuel.

The IPCC recommends use of an N_2O conversion factor for LCA modeling to estimate the amount of N_2O 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 a value in the range of the IPCC-recommended factor of 1.325%. The GREET model uses the IPCC value[289] and the GHGenius model uses a factor of 1.125%.[285] Using these relatively low conversion factors generally results in CI benefits for biodiesel pathways relative to conventional diesel. However, Crutzen et al.[287] concluded that the IPCC emission factor for N_2O was seriously underestimated, and recommended a conversion value equivalent to an IPCC factor of 2.24-3.74.[289] This change results in biodiesel pathways having increased GWP relative to conventional diesel. Delucchi's LEM model, which includes a more comprehensive nitrogen balance than other models, predicts a 50% increase in life-cycle GHG emissions for biodiesel relative to petroleum diesel, largely because of N_2O impacts.[290,288,291]

5.2.3 Co-Product Allocation Methods

Several co-products are produced throughout the manufacturing processes of biodiesel and renewable diesel. For example, a meal remains after extracting oil from any of the oilseeds and glycerin is produced during transesterification. Common practice in LCA modeling is to allocate some of the environmental impacts to these co-products if they have value elsewhere in the marketplace. Several allocation methods exist, as described below, and the choice of method is not uniform. [292,293,294].

- *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). This method provides a clear basis for allocation. However, it does not consider changes in scale, or the impacts that may be offset by replacement of other products.

- *Economic Allocation*—Calculations are performed on the basis of the economic value of the biofuel and other valuable by-products. The basis for economic allocation is not as clear, and requires some knowledge of market values of the products, which may change with time. This may be resolved through linkage to an economic model.

- *Expanded Allocation*—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. This method expands the boundaries of the LCA, so changes in assumptions may have significant effects on the results. Also, if no corrections are made for changes in scale, the evaluation may be meaningless for large scale productions, 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. This provides a simplified approach, but may be too simplistic.

Many LCA studies have shown that the choice of allocation method can significantly affect the final results. Bernesson, et al. studied the effects of all four allocation methods listed above, and found that the CI value can be reduced by 25-60% compared to no allocation.[292] A scan of LCA methodologies by Guinee and Heijungs found that different allocation methods could result in up to a 250-fold difference in extreme cases. [294]

To legitimately allocate environmental impacts to co-products, clear boundaries and allocation assumptions must be defined. Consideration must also be made for large-scale changes such as those influenced by changes in policies. For example, glycerin is a common biodiesel by-product that is credited with some of the environmental impact. However, as biodiesel production increases, the glycerin market may become saturated, causing a reduction in demand and prices. If no further use of the glycerin can be found, the by-product then becomes a waste product of the process, and none of the emissions should be attributed to it.

There are benefits and drawbacks to each of the co-product allocation methods described above. However, many of the policy-related LCA methodologies employ allocation by energy. [281,9,271,295]

5.3   Literature Review and Database Construction

Due to its increasing use in policies and growing debates and controversy, the literature regarding LCA of biofuels is expanding rapidly. For this literature review, the authors focused specifically on LCAs measuring the carbon intensity (CI) of biodistillates. The search was conducted through both Web of Science Journal Search, and through on-line "Google" searches. The keywords used included "biodiesel," "life-cycle-assessment," "LCA," "land-use-change," "indirect land use change," "biofuel," "greenhouse gas," "greenhouse gas accounting," "renewable diesel," and "carbon intensity." In addition, relevant citations made in journal articles or other reports were individually searched.

The literature search resulted in nearly 150 citations to review (including the original listing included in the CRC AVFL-17 study). The complete list of journal articles and relevant publications reviewed is included in Appendix X. A database of LCA results was constructed from this set of citations. Many of these resources were not complete LCA studies and were not included in the database from which the following tables and figures were generated: most of them discuss or describe methodologies and

approaches (in particular, many of them discuss the topic of ILUC). The database was populated with data from any relevant LCA studies that reported a carbon intensity (CI) value. The primary functional unit of the database was selected to be g $CO_{2\,eq}$/MJ $_{fuel}$. When possible, studies that reported in a different functional unit such as g $CO_{2\,eq}$/mi or g $CO_{2\,eq}$/kg were converted. The original units and conversion factors are noted in the database. (When possible, a conversion factor described in the paper was used. If none was mentioned, a standard conversion factor, such as the lower heating value of biodiesel, was used). Studies that could not be converted are so noted in the expanded database.

LCA studies that did not calculate a CI were not included in this database or assessment. This includes studies that only calculate a carbon payback period, or only determine energy return. Other studies that focused primarily on the biogenic emissions or those that are emitted during cultivation only, were also omitted from the database. Additionally, several studies evaluated overall environmental impacts by weighting impact categories such as eutrophication, acidification, ozone layer depletion, and human toxicity in addition to CI. [296,297] If these studies did not report a separate number for CI, they were not included in the database.

In Appendix X, a check mark in the column next to the citation indicates that the reference was included in the database. A total of 42 references are included in the complete database, which is provided separately in electronic format (Excel spreadsheet). Only 18 of these 42 studies were included in the previous AVFL-17 review. Several of the studies have since been updated. The studies with updated results replaced the older studies [298,299,300]. The electronic database is structured as a spreadsheet in which each result or scenario from a source has a row of data. The data include the following fields:

1. **Study Number**- identifying number used on charts and figures included in this report
2. **Primary Author**- the last name of the first author
3. **Year**- the year of publication
4. **Feedstock-** type of vegetable oil or animal fat used to produce the biodistillate fuel
5. **Location of production**- the location where the feedstock was grown
6. **Location of use-** location where the final product was used
7. **Production method**- to denote transesterification or hydroprocessing
8. **Fuel Name**- biodiesel, renewable diesel, or a uniquely-named renewable diesel
9. **Model used**- the LCA model or database used
10. **WTT/WTW** – "well-to-tank" or "well-to-wheels" to denote the boundaries of the modeled pathway
11. **Allocation method**- to denote the method of co-product allocation
12. **Scenario**- describes the situation, if more than one scenario is modeled in the study
13. **Functional unit**- the functional unit (FU) varied with publications. When possible, the units reported were converted to g $CO_{2,eq}$/MJ$_{fuel}$.
14. **Reference Land Use**- important for the estimation of soil carbon levels. For example, the land use could be virgin grass- or forest-lands, set-aside land, existing crop land, etc. Not all studies defined a reference land use.
15. **WTW Carbon Intensity-** The sum of all CI values (WTT + TTW when given as separate numbers) to give Well-to-Wheels (WTW) CI (in the FU noted).
16. **WTT Carbon Intensity –** the CI result of the fuel's growth, production, and storage stages (in the FU noted)
17. **TTW Carbon Intensity-** The CI result from combustion of the fuel.

18. **ILUC effects**- The CI resulting from any ILUC effects that were included.

19. **DLUC effects-** The CI resulting from direct land use change (DLUC) effects. In particular, studies that modeled cultivation on virgin lands had large DLUC effects.

20. **Total CI (including ILUC)-** the sum of the WTW CI and the ILUC and DLUC effects.

21. **Reference Fuel-** the CI value of the reference petroleum diesel fuel

22. **% Benefit-** a calculation of the reduction in CI relative to the reference fuel (Reference Fuel CI- Total CI)/ (Reference Fuel CI)

23. **& 24. ER** & **Reference ER**– Although energy return was not a focus of this work, values for the biofuel and reference fuels were noted here when included.

25.-32. **CI breakdown by Category-** the categories include: **Cultivation** (all agricultural inputs associated with growing the feedstock)**; N_2O emissions** (noted when given separately from cultivation); **Drying & Pressing, Transport** (from farm to oil mill and from oil mill to production location); **Oil Mill** (occasionally noted separately from drying & pressing; also includes rendering for tallow and yellow grease); **Production; Distribution** (includes transportation to re-fueling station, distribution and storage); and **Offsets** (any offsets noted due to allocation, CO_2 uptake, etc.)

33. **N_2O Conversion Factor-** Due to the significance of the N_2O conversion factor, and its effect on the final results, the value was noted when included.

34. **Original Units**- If the units had to be converted to g CO_2 $_{eq}$/MJ $_{fuel}$, the original unit was noted.

35. **Conversion Factor**- The conversion factor used to convert to g CO_2 $_{eq}$/MJ$_{fuel}$ was noted. When possible, the conversion factor was based on information provided in the paper. However, in some cases, a standard unit (i.e. the LHV of biodiesel) was used.

36. **Notes-** any additional notes to describe the paper and results.

This expanded database was then used to generate the summary database presented in Appendix XI, which gives a single "representative" CI value from each feedstock for each study. The representative value is an average (if multiple scenarios were given, but none was defined as a baseline), a single point (if only one value was given), or a baseline or best-case (if multiple scenarios were given, and one was selected as the defining case). The reference fuel value is also given, along with the percent benefit. Additionally, any effects from LUC are given along with a percent benefit after LUC is applied. Only data from the expanded database that are presented in terms of g CO_2 $_{eq}$/MJ$_{fuel}$ are given in Appendix XI. Additionally, other studies were excluded if they had unique or incomparable results. For example, Study No. 133 [301] only analyzed the WTT (without combustion), but included an offset for CO_2 uptake during cultivation (which is generally used to offset combustion emissions), thus making the results appear more favorable than is warranted.

5.4   Carbon Impact (CI) Results

5.4.1   Effect of Feedstock

The carbon intensity results from each study were segregated by feedstock type, and are shown graphically in Figure 19: (a) soybean, (b) rapeseed, (c) palm, (d) yellow grease, and (e) other oils. Each graph shows biodiesel (represented by square symbols) and renewable diesel (represented by triangles) for a given feedstock. Different colors in Figures 20 (a)-(d) represent different countries in which the fuel is used. In Figure 19 (e), the different colors represent different feedstocks; no further distribution by country is made.

A single point in Figure 19 indicates that only a single CI value was given. If multiple scenarios were considered, the minimum and maximum of the scenarios are represented as range bars, and the plotted point represents either a stated baseline case or an average of the scenarios. In some cases, range bars extend only in one direction and have a point on the upper end. This indicates that a LUC value was calculated in these cases; the lower point shows a representative value for the case(s) without LUC, while the 1-sided bar represents the impact with LUC (Note: these are applied to Study No. 74, 81, 83, 113, and 127). If more than one LUC case was estimated for a single feedstock in a single study, only the highest value is shown. To illustrate the impact relative to conventional diesel, the reference petroleum diesel value is shown by open circles. The numbering of the points refers to the Study Numbers defined in Appendix XI. Note that in Figures 20 (a) and (b), Study Nos. 8 and 9 were published in 2004, but are shown at a different time period so that identical chart axes could be used in all five charts of Figure 19.

(a)
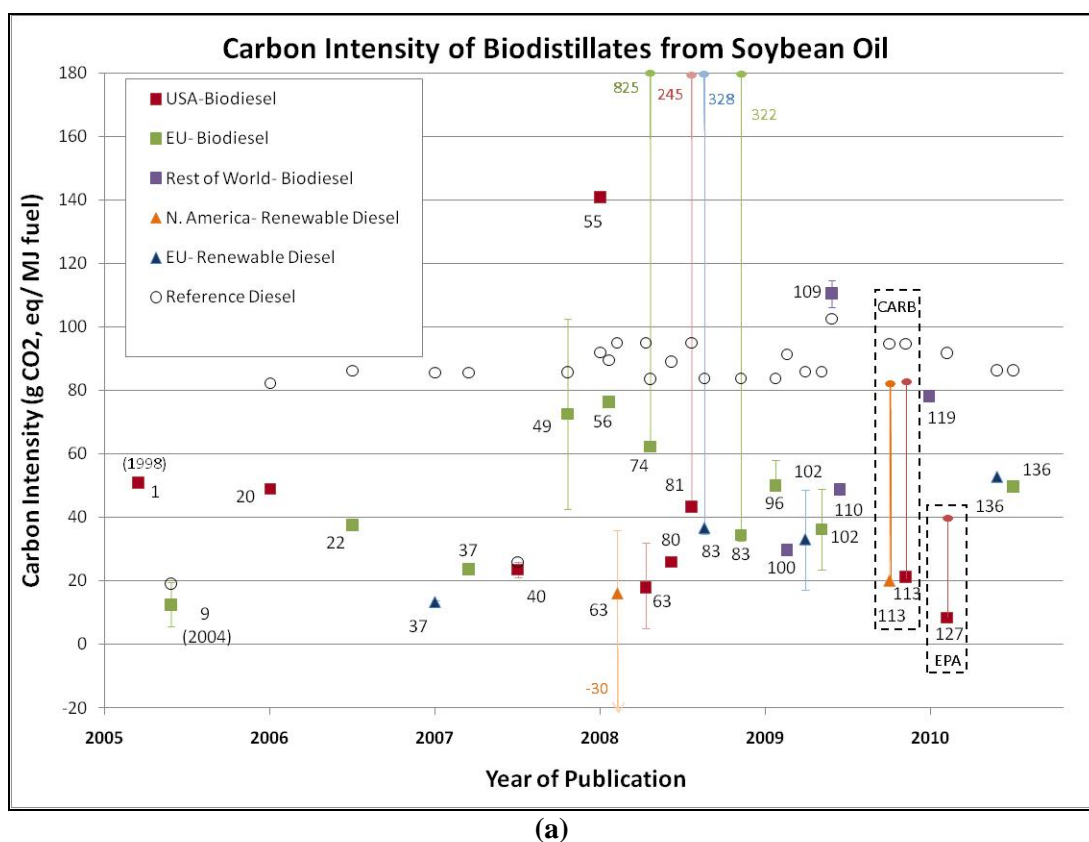
Figures 19 a,b,c,d,e. Carbon Intensity of Biodistillates in g CO_2,eq/MJfuel for: (a) Soybean Oil, (b) Rapeseed Oil, (c) Palm Oil, (d) Yellow Grease and Tallow, (e) Other Oils.

Square symbols represent biodiesel fuels: triangles represent renewable diesel. Range bars indicate that several values are given for more than one scenario. Large range bars in one direction indicate the influence of land use changes. Open circles represent the reference diesel value. The numbering refers to study numbers provided in Appendix XI.

120
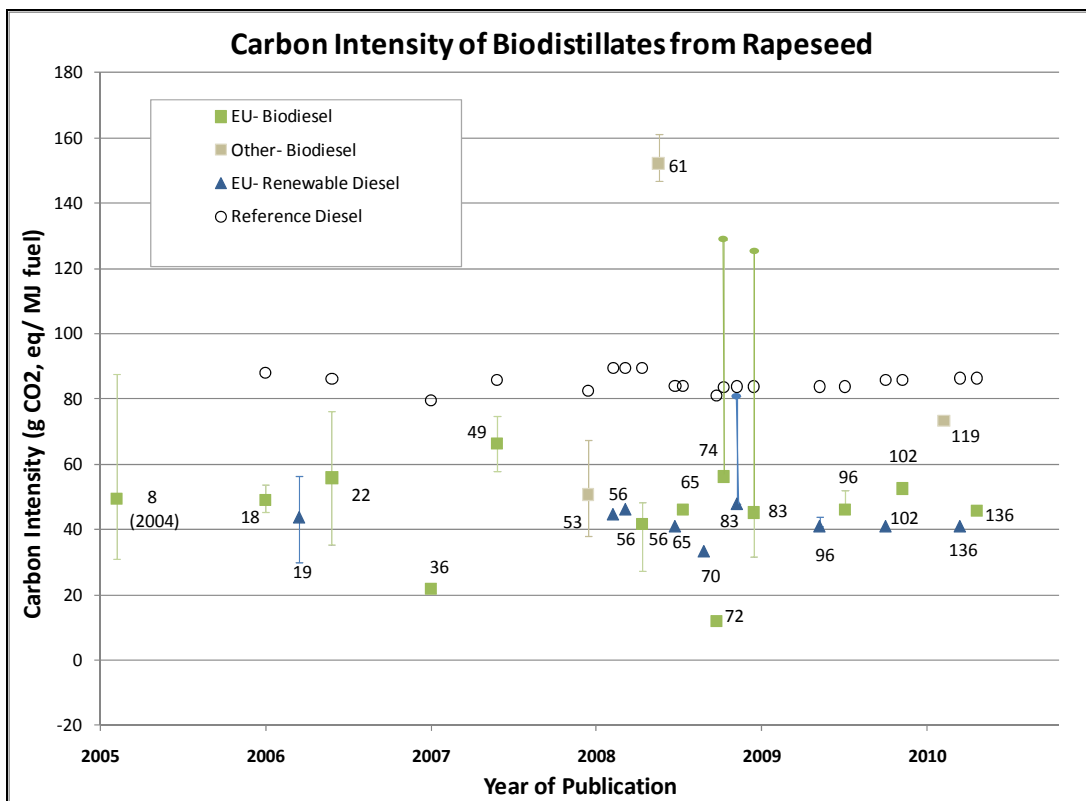
(b)
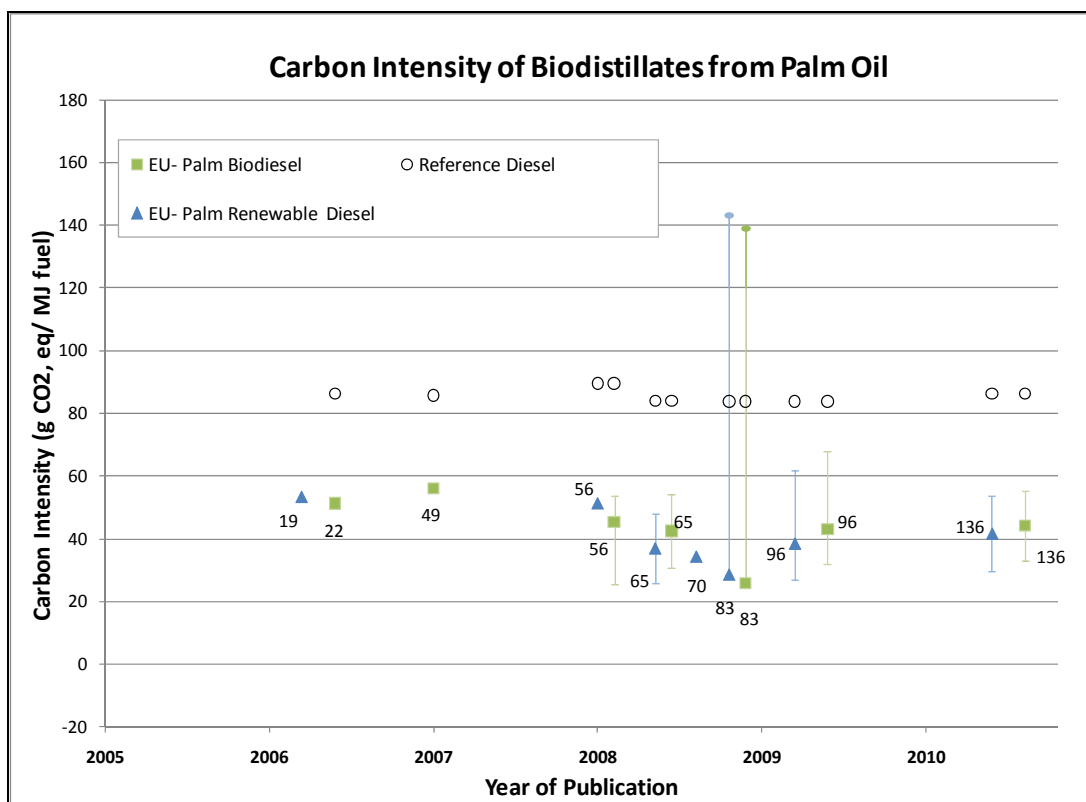
(c)
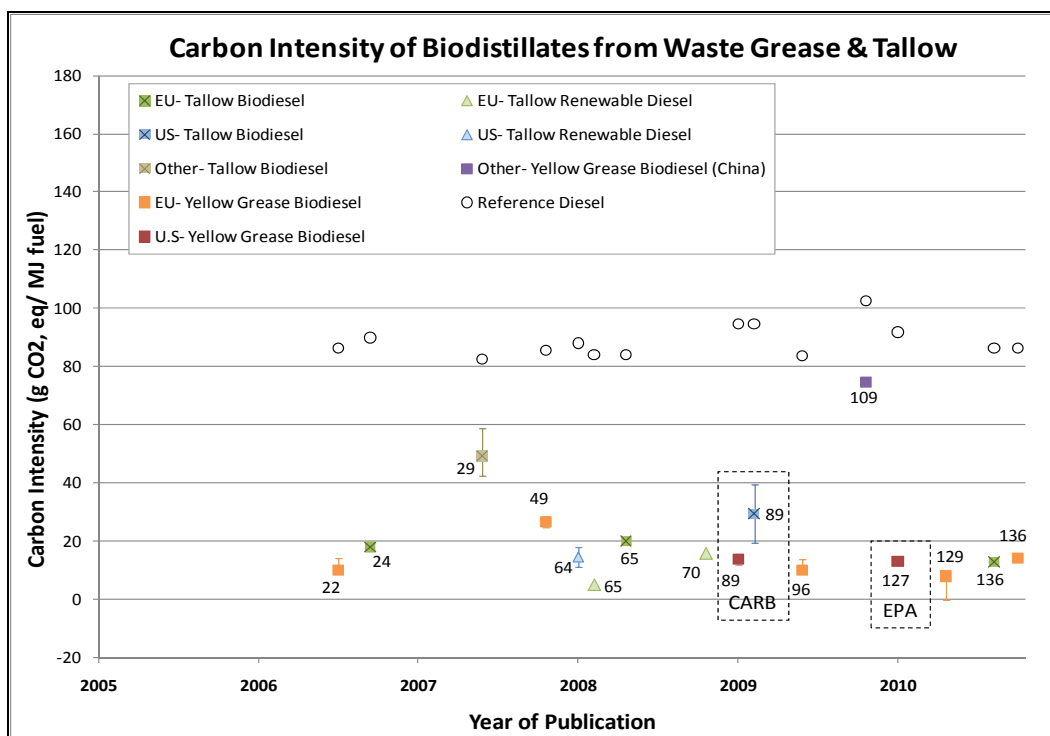
(d)
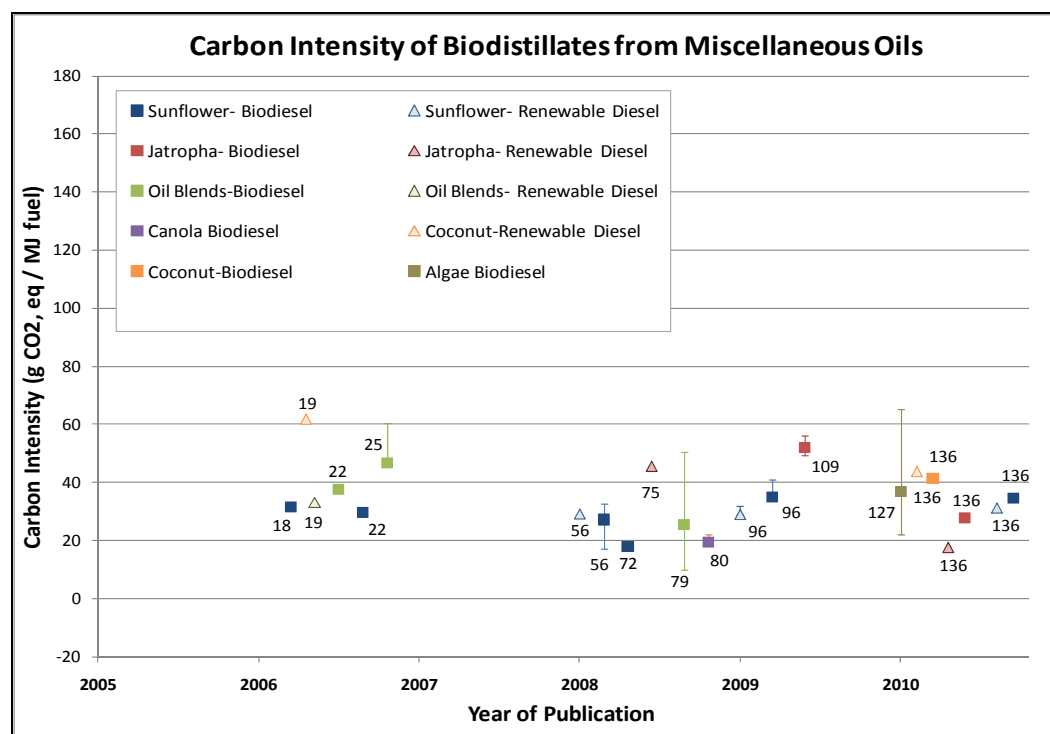
(e)

It is important to note that the agricultural practices of a region influence the biodistillate feedstock type. For example, soybean is the primary feedstock in the U.S., while rapeseed dominates in EU countries.

Since the EU does not produce much of its own soybean oil, it must be imported (likely from the U.S. or Brazil) if it is to be used as a biodiesel feedstock. This import issue leads to higher CI impacts from soy-derived biodiesel when used in the EU (or for rapeseed-derived biodiesel when used in the U.S.).

It is interesting to note that a few of the CI results shown in Figure 19(a) for soybean-derived biodistillate show large effects of ILUC. The CARB results from their LCFS regulations (Study No. 113) and the EPA results from their RFS2 regulations (Study No. 127) are also highlighted. These studies will be discussed in more detail later in Section 5.4.3.

5.4.2   Effect of Biodistillate Type

In an attempt to distinguish the effects of feedstock and fuel type, the LCA database was further sorted and parsed into separate categories for (a) soybean, (b) rapeseed, (c) palm, (d) tallow, (e) yellow grease, and (f) sunflower. Segments of the database for each of these feedstocks are presented in Appendix XII. The CI values shown here were determined from average scenarios for each feedstock and each fuel type (biodiesel and. renewable diesel).

This data sorting and parsing approach aids in identifying results that are very different from others. These "outlier studies," which are highlighted with shading in Appendix XII, were not included in the assessments of average CI benefits described below. Some of these outlier studies did not report a reference fuel for comparison. Other reasons for excluding specific studies are briefly listed below:

- Study No. 1 (Sheehan et al.) estimated only CO2 emissions, not total GHG expressed as CO2 equivalent. Additionally, it is unclear why the reference fuel has such a high CI value.

- Study No. 9 (Carretto et al.) estimates only the well-to-tank emissions of both fuels, excluding the combustion emissions for petroleum diesel, thus giving a very low CI result for the reference diesel fuel.

- Study No. 40 (Kreider and Curtiss) also excludes the combustion emissions from petroleum diesel, resulting in a very low CI value for the reference fuel.

- Study No. 55 (Delucchi) illustrates the importance of N2O conversion assumptions by using a particularly high conversion factor, resulting in an extremely high CI for biodiesel. While the "true" conversion factor for N2O is still under debate, this data point was eliminated from this assessment.

- Study No. 109 (Ou et al.) was eliminated as an extreme outlier with insufficient data to explain the high values.

- Study No. 127 (EPA) was eliminated due to the complexity in separating ILUC effects from the general life cycle. Because of offsets and credits partly due to ILUC, the total baseline CI value reported is quite low, and difficult to compare with other studies.

- Study No. 8 (Bernesson et al.) was eliminated because of the extremely high reference fuel CI value reported (217 g CO2,eq/MJfuel).

- Study Nos. 61 (Harding et al.), 119 (Su and Lee), 19 (Gartner et al.), and 70 (Nikander) were all eliminated because they do not report a reference fuel.

- Study No. 136 (Renewable Fuels Agency) was eliminated from both the biodiesel and renewable diesel averages because it reports a duplicate (or near duplicate) value as Study No. 96 (European Union), which is based on the same inputs.

In Figure 20, the average percent CI benefits of biodiesel and renewable diesel are plotted for each feedstock type. The error bars represent one standard deviation; the study count number is given along the x-axis. Although there seems to be a slight difference among the vegetable oil feedstocks (soy, rape, palm and sunflower), the differences are generally within the error bars, so it is difficult to ascertain if one is truly different from another. The deviation in the soybean biodiesel may also result from the wide variety of countries modeling soybean. However, rapeseed, palm oil and sunflower are modeled almost exclusively in the EU, which may reduce the variations in transport distances and other modeling assumptions. There may also be some national/regional differences in the assumptions being applied. For example, EU policy allocates emissions based on the energy content of the co-products, while US policy tends to model on mass, energy and economic values of co-products. This may result in higher variability in the soybean model results, which are derived mainly from U.S. studies.

As shown in Figure 20, waste products (tallow and yellow grease) exhibit somewhat higher CI benefits than vegetable oils for both biodiesel and renewable diesel. This is because no cultivation emissions are attributed to waste products, thus resulting in lower WTT CI values. Very few studies have been reported for renewable diesel made from waste products: only two for tallow, and none for yellow grease.
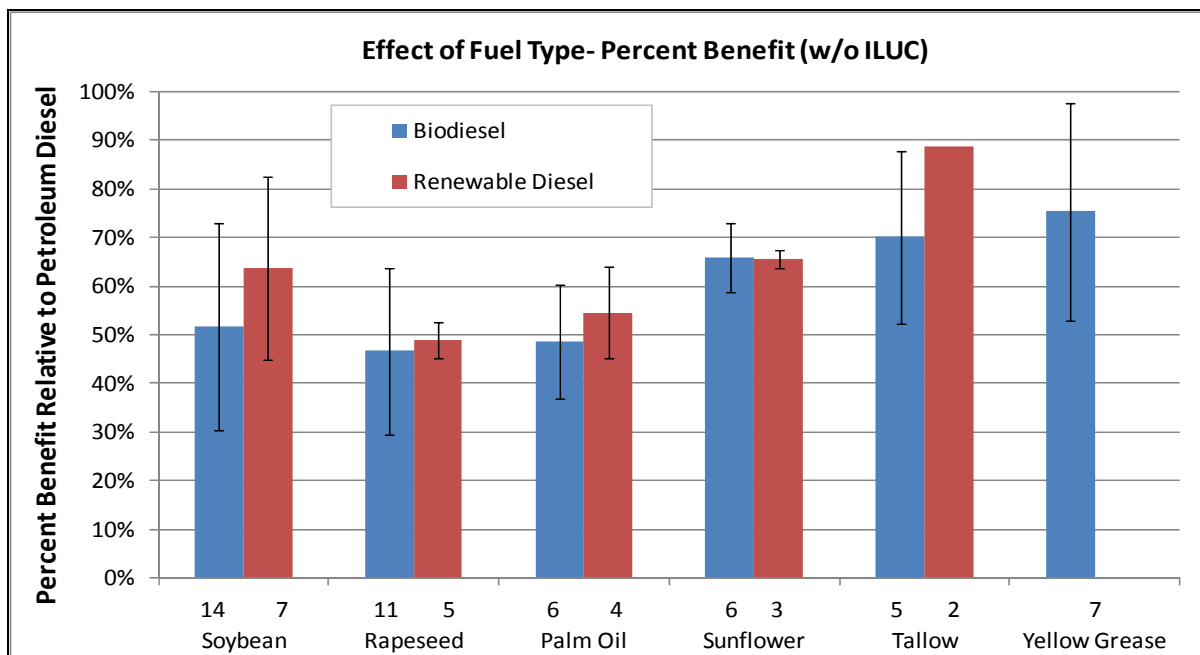
Figure 20. Carbon Intensity, % Benefit – Effect of Feedstock and Fuel Type
(Number under each bar represents the number of studies)

For most feedstocks, renewable diesel shows a slightly more favorable CI result than biodiesel. However, fewer studies have been completed for renewable diesel in general, and many of them are published by the renewable diesel industry. More sophisticated data analysis techniques (and a more robust database) would be required to clearly establish differences between biodiesel and renewable diesel cases.

5.4.3   Effect of ILUC

In the previous CRC AVFL-17 study, a literature review of biodistillate-related LCA models showed that replacing conventional diesel with biodiesel generally resulted in a GHG benefit. However, with only a few exceptions, none of the studies considered the effects of global supply and demand economics of the feedstocks and how that affects and changes global land use.

The topic of ILUC and how it should (or should not) be considered in policy has been growing in popularity, and has been the subject of numerous recent publications. However, only a handful of LCA studies include an estimation of ILUC, and many of these focus on ethanol. [302,284,303] For example, Study No. 141 (Tyner et al. [303]) showed that inclusion of ILUC results may still result in a GHG benefit for ethanol, although it is significantly reduced (only 8-17% benefit compared to gasoline). Study No. 66 (Keeney and Hertel [284]) showed that ILUC depends heavily on yield elasticity, acreage response elasticity, and bilateral trade elasticity in their GTAP model for U.S. ethanol policy.

Some LCA studies that consider ILUC for biodistillates were not included in this database due to differences in reporting values. These studies, however, all illustrate the significance of ILUC. For example, Fargione et al. (Study No. 57) show that a payback period as high as 423 years can result from growing palm in peatland rainforests (which stores high amounts of CO_2 in the vegetation and soils) to produce biodiesel, while soybeans grown on cerrado grassland (which stores significantly less CO_2) still take 37 years to payback [304]. Panichelli et al. (Study No. 110) also developed a model to estimate the carbon payback period of soy biodiesel including ILUC. [305] In their determination, the payback period ranges from 46 to 976 years for the best and worst case scenarios. Fritsche (Study No. 97) developed a deterministic approach to calculating ILUC, using existing data. [306] However, even when using a conservative estimate, the ILUC effects alone from rapeseed result in an exceedance of the EU allowable GHG threshold. Melillo et al. (Study No. 108) showed that only when integrating over a long enough time period (i.e. 100 years), do biofuels show an adequate GHG advantage over conventional fuels. [307] The variation in results of the studies clearly illustrates the difficulty in determining the true effects of ILUC.

The only studies to specifically calculate a CI value for biodiesel including ILUC are CARB (LCFS Study No. 89 [308]), EPA (RFS2 Study No. 127 [9]), and Searchinger (Study No. 81 [274]). Two additional studies estimate direct land use change (DLUC) in other parts of the world: Study No. 83 by UFOP for the German Biomass Sustainability Ordinance [309], and Study No. 74 by Reijnders and Huijbregts [310]. In these cases, the authors model DLUC in situations where the biofuels are produced on virgin lands (such as Asian Rainforests), resulting in a large, upfront emission of CO_2 which must be amortized over time. Because of their similarities to an ILUC approach, these two DLUC studies were also included in the database, and were used below in comparison to ILUC impacts. Details of the assumptions and results of each ILUC study are provided below in the Table XXIII.

Table XXIII highlights some of the critical assumptions required to determine the full extent of ILUC impacts. The total fuel volume increase is generally modeled for a complete policy to determine the interactions between different land use changes and determine how much land will be affected. The type of land, and its soil and vegetation characteristics, are important in determining the GHG impacts from converting the lands to other purposes. Accounting for soil carbon stock is significant for both direct and indirect land use changes [311]. Changes to the land or tillage practices affect the soil carbon, so varying agricultural practices and cropland management can have a significant impact on GHG balance of biofuels crops, and can affect how significant the ILUC impacts are [302]. The time horizon and discount rate are also significant assumptions that can affect the final results. EPA and CARB have both settled on using a 30-year time horizon with a 0% discount rate.

The LCAs employed for policy tend to be the most detailed since they rely heavily on reviewer and stakeholder comments and inputs. The EPA offers one of the most detailed discussions of LCA modeling, likely due to the complexity in its evaluation and linking of numerous models. EPA's approach is to compare differences in emissions from a scenario in which the EISA policy biodiesel volume requirements are implemented and one in which they are not. The comparisons are made in 2022, the target year for full implementation. To determine the effects that could be attributed to each type of fuel, an incremental volume of each fuel was modeled while holding all other factors constant. For the

biodiesel case, a volume increase of 0.5 billion gallons from soybeans was used (representing a difference between 0.1 billion gallons in the 'business as usual' case, and a total volume of 0.6 billion gallons soy biodiesel in 2022).

Table XXIII. Assumptions for Studies Including Land Use Change Effects

Study No. Name	89 CA-LCFS	127 EPA-RFS2	81 Search- inger	83 German BSO[E]			74 Reijnders[E]	
Baseline Year	2001	2022[A]	2015				2007	2007
Feedstock	Soybean	Soybean	Soybean	Soybean	Rapeseed	Palm Oil	Soybean	Rapeseed
Volume Increase (Billion gal)	0.995	0.5	0.26	8 gal	8 gal	8 gal	/MJ fuel	/MJ fuel
Time Horizon (years)	30	30	30	20	20	20	10-25yrs	10-25yrs
Discount (%)	0	0	0	0	0	0	0	0
Land Use Increase (million ha)	0.94	1.1	0.79	.0607 ha[F]	.02 ha[F]	0.0079 ha[F]		
Type of Land Use Increase	~30% forest 70% pasture; 18% domestic	68% domestic	5% domestic; 45% Latin America[D]	Latin America-Savannah	EU-Grassland	SE-Asia-Rain Forest	Brazilian Rainforest	EU- Arable Land
% LUC attributed to biofuel	20%	Economic[B]	19%	27.70%	59.70%	48%	45%	73%
Carbon Payback Period, years	N/A	9[C]	NA	NA	NA	NA	NA	NA
CI from ILUC (g CO$_2$ eq/ MJ fuel)	62	31.9	205	289.6	32.8	112.8	511.7[G]	62.05[G]
CI w/o ILUC (Biodiesel)	21.25	7.9	43.4	32.4	45.2	25.9	63.2[H]	56.2[H]
Total CI (g CO$_2$ eq/ MJ fuel)	83.25	39.8	248.4	322	78	138.7	574.9	118.25
Reference Diesel Value	94.71	91.8	95	87.2	86.2	88.2	83.6	83.6
% Benefit w/o ILUC	77.6%	91.4%	54.3%	62.8%	47.6%	70.6%	24.4%	32.8%
% Benefit w/ ILUC	12.1%	56.6%	-161.5%	-269.3%	9.5%	-57.3%	-587.7%	-41.4%

[A] EPA compares results with and without EISA implementation in year 2022.

[B] Changing allocation based on price fluctuations in FASOM and FAPRI models

[C] Midpoint carbon payback period, low and high are 5 and 21 years, respectively

[D] Only describes location, not the type of LUC

[E] Studies measure the "direct" impacts of growing feedstocks in virgin lands. This can be considered ILUC, since no further land use change should occur if new feedstocks/ oils are being produced: they do not displace existing demands.

[F] The BSO model is based on an incremental use of 1GJ of RME, not a complete policy volume requirement.

[G] Average of a range of scenarios, including N$_2$O emissions conversion ratios varying from 1.5-5%, 10 year vs. 25 year time horizon, and tillage vs. no tillage practices.

[H] CI w/o ILUC includes fossil emissions only, other 'biogenic' emissions (i.e. fertilizer use, soil carbon, etc) is included as part of the 'direct' LUC- reported here as an 'indirect' LUC

EPA's approach combines several modeling methodologies as described in Section 5.2.1. This approach highlights the most important aspects of ILUC by including the extent, type and location of land conversion, as well as the emission factors from each type of land. To analyze these factors, EPA combined MODIS satellite imagery (called the Winrock data) to determine types of land in key agriculturally producing countries, and estimated emission factors for each type of land (e.g.. savannah, rainforest, grassland, etc.) The FAPRI model was then used to project location-specific increases in crop-land as a response to changing supply and demand of feedstocks. Because this modeling approach is so complex, the results are more difficult to separate into categories consistent with other studies. In addition to farming inputs, production, transport, tailpipe emissions and ILUC, EPA also estimates changes to domestic soil carbon, livestock, and rice methane emissions (all of which decrease, resulting in lower

GHG emissions) and international livestock and rice methane emissions (which decrease and increase, respectively).

The most representative CI breakdown of the EPA's LCA categories for biodiesel is shown in Figure 21. The categories that gave decreased emissions are represented in the "offsets" bar. The overall result from this soy-based biodiesel scenario (including ILUC of 31.9 g $CO_{2\ eq}/MJ_{fuel}$) shows a CI value of 39.8 g $CO_{2\ eq}/MJ_{fuel}$, compared to a reference diesel fuel baseline of 91.8 g $CO_{2\ eq}/MJ_{fuel}$. Therefore, soy-based biodiesel is determined by EPA to provide a 57% reduction in GHG on a life-cycle basis, which meets the required threshold value of 50% for biomass-based diesel fuel defined in the RFS2 regulations. EPA also completed studies for biodiesel from waste grease and algae, though neither of these fuels have ILUC associated with them.

The effects of ILUC are modeled independently in the CARB study (Study No. 93 [298]) and then added to the standard life cycle effects for biodiesel from soybeans grown in the Midwest as shown in Figure 21. CARB modeled a final volume of 1.0 billion gallons of biodiesel (consistent with the RFS2 requirement) beginning in 2001, when the production volume was 0.005 billion gallons. Thus, the complete volume increase modeled by CARB was 0.995 billion gallons. Sensitivity analyses were performed on inputs such as crop yield elasticity (which describes how the crop yield fluctuates with changes in price), elasticity of crop yields with respect to area expansion (which considers that yields on newly converted lands are different than on existing cropland), and elasticity of land transformation (which measures the extent which expansion into forestland and pastureland occurs due to increased demand on agricultural lands).
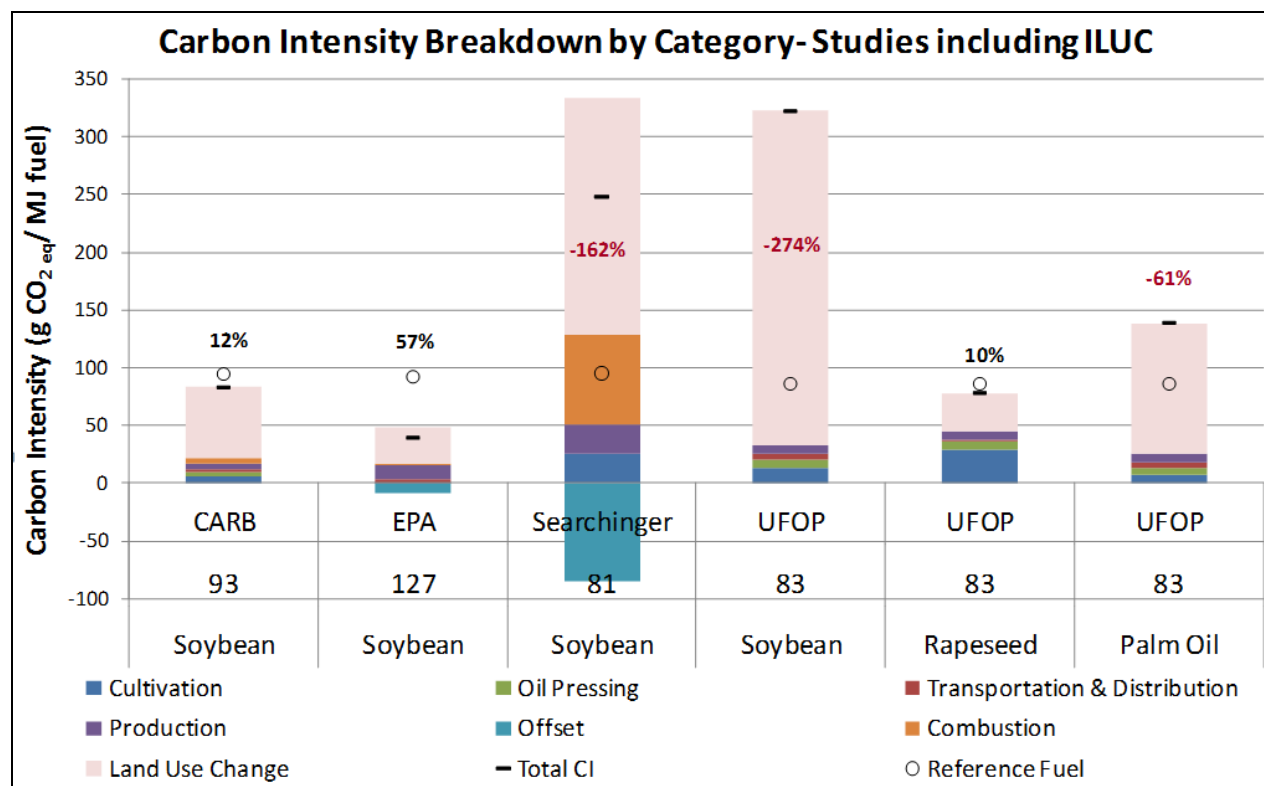
Figure 21. Carbon Intensity Breakdown by Life-Cycle Stage – Impact of ILUC on Biodiesel
(Number under each bar indicates Study No. – see Appendix XI.)

CARB's computed indirect land use CI ranged from 43 to 93 g $CO_{2,eq}$/MJ$_{fuel}$,. An average value for all cases was determined (for total land conversion area of 0.94 million hectare), and was adjusted to 62 g $CO_{2,eq}$/MJ$_{fuel}$ to account for yield increases between 2001 and 2004. Applying this ILUC CI to the biodiesel baseline LCA value of 21.25 g $CO_{2,eq}$/MJ$_{fuel}$ gives a total CI of 83.25 g $CO_{2,eq}$/MJ$_{fuel,}$ which represents a 12.1% reduction from the petroleum diesel base. (Note: In a previous CARB study, the ILUC value used was 42 g $CO_{2,eq}$/MJ$_{fuel}$, and the biodiesel base LCA value was 26.93 g $CO_{2,eq}$/MJ$_{fuel}$, which resulted in a 27% benefit relative to petroleum diesel at 94.71 g $CO_{2,eq}$/MJ$_{fuel}$ {Prabhu, 2009 21305 /id}). For renewable diesel produced from Midwest soybeans, CARB used a biodiesel baseline LCA value of 21.16 g $CO_{2,eq}$/MJ$_{fuel,}$ and applied the same ILUC value of 62 g $CO_{2,eq}$/MJ$_{fuel}$, to give a total CI of 82.16 g $CO_{2,eq}$/MJ$_{fuel,}$ which represents a 13% reduction in CI compared to the petroleum diesel base.

CARB also evaluated biodiesel from yellow grease and renewable diesel from tallow. However, since both are considered waste products, no effects from ILUC were attributed to these fuels, resulting in CI benefits of almost 90% for yellow grease biodiesel, and about 80% for renewable diesel from tallow.

Searchinger was one of the first proponents for ILUC [313], stating that all carbon uptake is indirect, so if indirect effects are not included, biofuels cannot reduce GHGs.[314] He argues that GHG emissions from combustion of biofuels impact the atmosphere the same way that emissions from fossil fuels do, but that a partial offset of the biofuel emissions is warranted in situations where additional carbon is generated – meaning carbon that plants would not have absorbed from the atmosphere in the absence of the biofuel. Therefore, he argues that the "carbon-neutral" principle as frequently used to promote biofuels is overly-simplistic and incorrect.

The CI breakdown chart shown in Figure 21 depicting Searchinger's LCA study (Study No. 81) includes a sizable positive value for combustion GHG emissions (orange bar segment), along with an equally-sizable negative offset for plant uptake of GHG. From Figure 21, it is also apparent that the base life-cycle emissions (from cultivation, production, etc.) are nearly double that from the CARB study (43.4 vs. 21.25 g$CO_{2,eq}$/MJ). Although the paper does not give details on assumptions, Searchinger used the GREET model to determine the fuel-cycle LCA while CARB used a slightly modified version of GREET. Searchinger also concluded that a significant increase in CI occurred because of indirect land use changes required to increase production of soy biodiesel. The specific types of land conversion were not defined, although the locations of conversion were described. Land in Southeast Asia made up roughly 20% of the total land converted, but produced almost 50% of the total emissions. Land conversion in Latin America made up about 45% of the total, and produced about 35% of the total emissions. Because of this large ILUC effect, Searchinger's final result indicated that the total CI value for the soybean-based biodiesel scenario was much higher than the companion petroleum diesel base case.

Studies No. 83 and 74 ([309,310]) both measure direct emissions. However, they both illustrate the importance of the type of land that is converted. In Studies 81, 93, and 127, a mix of land in a variety of locations is modeled, so it is difficult to ascertain the influence of each individual type of land. However, Studies No. 74 and 83 model the conversion of a particular type of land required to produce and use a single unit of fuel.

In Study No. 83 for soybean biodiesel, feedstocks from both North America and Latin America were investigated. The ILUC value illustrated in Figure 21 the high value for Latin America (290 g CO_{2eq}/MJ$_{fuel}$). While the baseline CI for either location is approximately the same (36 and 33 g CO_{2eq}/MJ$_{fuel}$, respectively), the ILUC varies significantly: from 55 for the N. American case to 290 for the Latin American case. Similarly a high ILUC CI impact of 113 g CO_{2eq}/MJ$_{fuel}$ was estimated for palm oil, which was assumed to involve expansion of agriculture into Southeast Asian rainforests. Rapeseed biodiesel is the only one to show a GHG benefit, however small. In this case, the rapeseed is assumed to be grown

locally, on EU croplands. The ILUC effects, however, still decrease the benefit from 48% to less than 10% for the default case.

Similarly in Study No. 74, Reijnders and Huijbregts calculated DLUC emissions from expanding croplands into either Brazilian Rainforests (for soybeans) or arable lands in the EU (for rapeseed). Again, the results illustrate the importance of the type of land that is converted. However, for this study, growing rapeseed on arable lands still produced a negative benefit relative to petroleum fuels, due to the land use change impacts.

While very few studies model ILUC, there are significant discrepancies among those that do. To fully understand these differences and make robust analyses of ILUC, a transparent data set and model boundaries must be described. Additionally, while many agree that agriculturally-related ILUC is important, other drivers for land use change also exist, such as socio-economic changes, technological changes, and population changes. [315]

6. REGIONAL FUEL SPECIFICATIONS AND QUALITY

6.1 Biodiesel Standard Specifications

One of the principal means of ensuring satisfactory in-use biodiesel fuel quality is establishment of a rigorous set of fuel specifications. As already discussed, the two most common biodiesel standards are ASTM D6751 (in the U.S.) and EN 14214 (in the European Union). Many other countries have defined their own standards, although in most cases, these standards are derived from either ASTM D6751 or EN 14214. Some countries have also worked together to define guidelines for regional biodiesel standards. For example, a group called the Asia-Pacific Economic Cooperation (APEC) issued a report in 2007 that addressed guidelines for standardizing biodiesel standards within the APEC region.[316]

Table XXIV identifies 17 different biodiesel standards pertaining to numerous countries around the world. The specification values included in the 17 standards are shown in Table XXIV. The sources of information for these standards are also provided in Table XXIV, many as links to websites. It should be mentioned that in many countries, biodiesel standards are evolving, with modifications occurring frequently. Thus, some of the specifications shown in Table XXV may no longer be current. Also, some countries directly link their standards to ASTM D6751 or EN 14214, though it is not always clear whether updates to these standards occur automatically as the ASTM and EN standards change. For example, some sources state that China's biodiesel standard is "identical to ASTM," yet the most recent specification values that could be located (shown in Table XXV) are not consistent with current ASTM values. Other sources state that China's biodiesel standard "is deemed to be a recommended standard, which biodiesel manufacturers are encouraged to comply with."

6.2 Quality Control/Quality Assurance

Another means of ensuring satisfactory biodiesel product quality involves establishment and enforcement of quality control/quality assurance (QC/QA) programs. As early as 1999, the German Association for Quality Management of Biodiesel (abbreviated AGQM in German) was established to deal with in-use fuel quality.[317] In the U.S., the National Biodiesel Board has addressed the issue of QC/QA by establishing the National Biodiesel Accreditation Commission that oversees and directs the BQ-9000 Quality Management System.[318] This Commission has now issued three sets of requirements: one for biodiesel producers,[319] one for biodiesel marketers,[320] and one for biodiesel laboratories.[321] The BQ-9000 Program includes a combination of ASTM standards and a quality systems program that includes storage, sampling, testing, blending, shipping, distribution, and fuel management practices. By following these requirements, the company – not the fuel – receives accreditation.

6.3 In-Use Handling Guidelines

Several organizations have defined in-use handling guidelines to help ensure satisfactory biodiesel quality in the marketplace. For example, NREL has issued a number of guidelines, with the latest edition being released in early 2009.[45] More recently, CONCAWE issued a set of guidelines for handling and blending FAME in the European situation.[46] This report discusses the following major fuel quality concerns, and offers suggestions for mitigating each one:

- Stability and deposit formation
- Cold temperature handling and operability
- Solvency
- Microbial contaminants
- Water separation
- Material compatibility

6.4 Fuel Quality Surveys

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, who collected and analyzed 27 samples of B100 and 50 samples of B20.[322] Results showed that 85% of the B100 samples met all ASTM D6751-03 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 yet included in ASTM D6751 at the time of this study; it 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 – with 7 being considerably higher and 11 being considerably lower than this range.

NREL conducted another nationwide fuel quality survey of B100 in 2006.[323] Specification testing of 37 samples showed that 59% failed to meet the ASTM D6751 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 somewhat 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.[324] 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 D6751 specifications. Biodiesel 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 D6751 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, NREL concluded that 90% of B100 produced in the U.S. in 2007 met all specifications; a significant improvement over previous survey results. However, an important point to remember is that all B100 samples in the 2007 survey were voluntarily provided by willing producers. In the earlier surveys, samples were obtained from blenders

and distributors, not from producers. This change in procedure could raise questions about sampling bias. the authors are not aware of any systematic biodiesel field surveys being conducted (in the U.S. or elsewhere) since the 2007 NREL survey.

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. Other organizations have 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.[325] This study also reinforced concerns about oxidative stability, as 45% of the samples failed to meet the Rancimat test specification. Very recently, NREL conducted a field quality survey of 40 biodiesel blends (mostly B6-B20) collected in the winter of 2009-2010. [326] While not yet published, initial results are encouraging in showing improved fuel quality compared to previous surveys.

In another recent report, a ^{14}C radiocarbon analysis method was developed and applied to U.S. biodiesel samples acquired in 2006.[327] 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.[328,329] 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 D7467-08) specifies use of method D7371, which utilizes mid-infrared spectroscopy.[48]

Other spectroscopic methods utilizing near IR,[330] UV,[331] and visible light [332] have also been used with some success. 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.[333,334]

Table XXIV. Sources of Information for Biodiesel (B100) Standard Specifications

Country	Standards	Source
Argentina	Resolution 1283/2006	http://www.dieselnet.com/standards/ar/fuel.php
Australia	Department of Environment, Water, Heritage and the Arts	http://www.environment.gov.au/atmosphere/fuelquality/publications/draft-standard.html
Austria	ON C1191	http://www.svlele.com/biodiesel_std.htm
Brazil	B100- ANP Resolution 42/2004	http://www.dieselnet.com/standards/br/fuel.php http://ec.europa.eu/energy/renewables/biofuels/doc/standard/2007_white_paper_icbs.pdf
China	GB/T 20828	www.nist.gov/oiaa/LiHongmei.pdf http://www.bioenergytrade.org/downloads/tsukuba20kaochinabiodieselfeedstockmarket.pdf
Colombia	Resolution 180782; Feb 1, 2007	http://www.minminas.gov.co/minminas/kernel/usuario_externo_normatividad/form_consultar_normas.jsp?parametro=1372&site=17
India	IS15607:2005	http://www.tistr.or.th/APEC_website/Document/2nd%20APEC%20biodiesel/2nd%20APEC%2016Jul%2008/7.%20Biodiesel%20Situation%20in%20India.pdf http://www.svlele.com/biodiesel_std.htm
Germany	DIN V 51606	http://www.biodiesel-fuel.co.uk/biodiesel-standards/
Indonesia	SNI 04-7182-2006	http://www.biomass-asia-workshop.jp/biomassws/05workshop/program/10_Priyanto.pdf
Japan	(JIS K2390)	http://www.dieselnet.com/standards/jp/fuel_biodiesel.php
New Zealand	Regulation SR 2008/138	http://www.legislation.govt.nz/regulation/public/2008/0138/latest/DLM1325297.html?search=ts_regulation_Engine+Fuel_resel
Philippines	DPNS/DOE QS 002:2007	http://www.doe.gov.ph/popup/dpns%20doe%20qs%20002%202007.pdf
South Africa	SANS 1935:2004	http://www.satobiodiesel.co.za/lit_quality.html
Taiwan	CNS 15072K5155	http://www.biofuels.apec.org/pdfs/ewg_biodiesel_standards.pdf
United States	ASTM D6751	http://www.biodiesel.org/pdf_files/fuelfactsheets/BDSpec.PDF http://www.astm.org/Standards/D6751.htm
European Union	EN 14214	http://www.biodiesel-fuel.co.uk/biodiesel-standards/
Worldwide Fuel Charter	Biodiesel Guidelines (2009)	http://www.cvma.ca/eng/publications/B100_Guideline_final_26Mar09.pdf

Table XXV. Biodiesel (B100) Standard Specifications

Property	Argentina	Australia	Austria	Brazil	China[e]	Colombia	European Union	Germany	India
Water and Sediment (% vol., max.)	0.05	0.05		0.02		0.05	0.05	0.03	0.05
Total Contamination (mg/kg, max.)						500	24	20	
Kinematic Viscosity @ 40° C (mm^2/s)	3.5 - 5.0	3.5 - 5.0	3.5 - 5.0		1.9 - 6.0	1.9 - 5.0	3.5 - 5.0	3.5 – 5.0	2.5 - 6.0
Flash Point, Closed Cup (°C, min.)	100	120	100	100	130	120	120	110	120
Methanol (wt.%, max.)			0.2			0.2	0.2	0.3	0.2
Cetane No. (min.)	45	51	49	45	49	47	51	49	48
Cetane Index (min.)						49			
Cloud Point (°C, max.) [c]				Report		Report	Variable		
Pour point, (°C, max.) [c]						Report			
CFPP (°C, max.) [c]		Report	≤ 0		Report	Report			
Sulfated Ash (wt.%, max.)		0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02
Total Ash (wt.%, max.)									
Gp I metals Na + K (mg/kg, max.)		5.0		10		5.0	5.0		Report
Gp II Metals Ca + Mg (mg/kg, max.)		5.0					5.0		Report
Total Sulfur (ppm, max.)	10	10	100	10	50	10	10	10	50
Phosphorous (ppm, max.)	10	10	20	10		10	10	10	10
Acid No. (mg KOH/g, max.)	0.5	0.8	0.8	0.8	0.8	0.8	0.5	0.5	0.5
Carbon Residue (wt. %, max)		0.05	0.05	0.05	0.3 [b]	0.3 [b]	0.3 [b]	0.05	0.05
Free Glycerin (wt.%, max.)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total Glycerin (wt.%, max.)	0.24	0.25	0.24	0.38	0.24	0.25	0.25	0.25	0.25
Mono-Glyceride (wt.%, max.)				1.0			0.8	0.8	0.8
Di-Glyceride (wt.%, max.)				0.25			0.2	0.4	
Tri-Glyceride (wt.%, max.)				0.25			0.2	0.4	
Distillation (T-90 °C, max.) [d]		360		360 (T-95)		360			
Copper strip corrosion (3-hr. at 50°C, max.)	Class 1	Class 1		No. 1	No. 1	No. 1	No. 1	No. 1	No. 1
Oxidation Stability (hrs @ 110°C, min.)	6	6		6	6	6	6		1.5
Linolenic acid methyl ester (wt.%, max.)							12.0		
Polyunsaturated acid methyl esters (wt.%,max)							1.0		
Ester Content (wt.%, min.)	96.5	96.5				96.5	96.5		96.5
Iodine Number (g I$_2$/100g, max.)	135		120			120	120	115	115
Density (kg/m^3)	875 - 900	860 - 890	850 - 890		820 - 900	860 - 900	860 - 900	875 – 900	860 - 900
Cold Soak Filterability (seconds, max.)									

Notes:
a) Alternatively, flash point must be > 130°C

b) This limit is based on the bottom 10% fraction of the fuel

c) Low temperature properties are generally not specified, but should be reported

d) Atmospheric equivalent T-90 point

e) No specific requirements found, but China standard GB/T 20828 is said to be identical to ASTM.

Table XXV. Biodiesel (B100) Standard Specifications (cont.)

Property	Indonesia	Japan	New Zealand	Philippines	South Africa	Taiwan	United States	Worldwide Fuel Charter
Water and Sediment (% vol., max.)	0.05	0.05	0.05	0.05	0.02		0.05	0.05
Total Contamination (mg/kg, max.)		24	24		24	24		24
Kinematic Viscosity @ 40° C (mm^2/s)	2.3 - 6.0	3.5 - 5.0	2.0 – 5.0	2.0 - 4.5	3.5 - 5.0	3.5 - 5.0	1.9 - 6.0	2.0 - 5.0
Flash Point, Closed Cup (°C, min.)	100	120	100	100	100	120	93	100
Methanol (wt.%, max.)		0.2		0.2	0.2	0.2	0.20 [a]	0.2
Cetane No. (min.)	51	51	51	51	45	51	47	51
Cetane Index (min.)		51						
Cloud Point (°C, max.) [c]	18	Report		Report			Report	
Pour point, (°C, max.) [c]								
CFPP (°C, max.) [c]						0		
Sulfated Ash (wt.%, max.)	0.02	0.02	0.02	0.02	0.02		0.02	0.005
Total Ash (wt.%, max.)						0.02		0.001
Gp I metals Na + K (mg/kg, max.)		5.0	5.0	5.0	10	5.0	5.0	5.0
Gp II Metals Ca + Mg (mg/kg, max.)		5.0	5.0	5.0	5.0	5.0	5.0	5.0
Total Sulfur (ppm, max.)	100	10	10	500	10	10	15	10
Phosphorous (ppm, max.)	10	10	10	10	10	10	10	4
Acid No. (mg KOH/g, max.)	0.8	0.5	0.5	0.5	0.8	0.5	0.5	0.5
Carbon Residue (wt. %, max)	0.05	0.3 [b]	0.05	0.05	0.05	0.3 [b]	0.05	0.05
Free Glycerin (wt.%, max.)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total Glycerin (wt.%, max.)	0.24	0.25	0.25	0.24	0.38	0.25	0.24	0.24
Mono-Glyceride (wt.%, max.)		0.8	0.8	0.8	1.0	0.8		0.8
Di-Glyceride (wt.%, max.)		0.2	0.2	0.2	0.25	0.2		0.2
Tri-Glyceride (wt.%, max.)		0.2	0.2	0.2	0.2	0.2		0.2
Distillation (T-90 °C, max.) [d]	360	360		360	360 (T-95)		360	
Copper strip corrosion (3-hr. at 50°C, max.)	No. 3	No. 1	No. 1	No. 1	No. 1	No. 1	No. 3	Light Rusting
Oxidation Stability (hrs @ 110°C, min.)		2	6	6	6	6	3	10
Linolenic acid methyl ester (wt.%, max.)		12.0	12.0		12.0	12.0		12.0
Polyunsaturated acid methyl esters (wt.%,max)		1.0	1.0		1.0	1.0		1.0
Ester Content (wt.%, min.)	96.5	96.5	96.5		96.5	96.5		96.5
Iodine Number (g I$_2$/100g, max.)	115	120	140		140	120		130
Density (kg/m^3)	850 - 890	860 - 900	860 – 900	860 - 900	860 – 900	860 - 900		860 - 900
Cold Soak Filterability (seconds, max.)							360	

Notes:
a) Alternatively, flash point must be > 130°C

b) This limit is based on the bottom 10% fraction of the fuel

c) Low temperature properties are generally not specified, but should be reported

d) Atmospheric equivalent T-90 point

e) No specific requirements found, but China standard GB/T 20828 is said to be identical to ASTM.

7. SUMMARY AND CONCLUSIONS

7.1   Biodiesel Composition

Although the literature indicates considerable variability, there is growing consensus regarding the fatty acid (FA) profiles of vegetable oils and animal fats commonly used to produce fatty acid methyl esters (FAME). Clear differences in carbon chain length and degree of unsaturation are apparent from one feedstock to the next. These differences influence the properties and performance of biodiesel (FAME) and biodiesel blends.

The compositional profiles of common vegetable oils are dominated by five fatty acid species: palmitic (16:0), stearic (18:0), oleic (18:1), linoleic (18:2), and linolenic (18:3). Coconut oil is significantly different, containing large fractions of lighter fatty acid species – especially lauric (12:0) and myristic (14:0). Camelina is also somewhat different from most other vegetable oils, with linolenic acid (18:3) being its largest single constituent, along with smaller amounts of the heavier species, 20:1 and 22:1.

Jatropha also appears somewhat unusual in that it contains a significant level (2-3%) of a high molecular weight FA, lignoceric acid (24:0). However, this result is quite uncertain – with only a few literature reports mentioning this substance – and requires further confirmation. If confirmed, this could raise concerns about low temperature operability of Jatropha-derived FAME.

Compared to vegetable oils, relatively little detailed compositional information is available for algal lipids. FA compositional profiles have been determined for very few of the over 40,000 identified algal species. However, it is clear that compositional variability across different algal species can be extreme. Some species have a wider range of FA chain lengths than is typical for vegetable oils. Some species have much higher levels of unsaturation – and especially multi-unsaturation – than is typical for vegetable oils. The high variability in algal lipid composition is partly due to the fact that compositions vary with growth conditions.

7.2   Biodiesel Properties

The physical and chemical properties of a biodiesel are determined by its chemical composition. Due to its considerable oxygen content (typically about 11%), biodiesel has lower carbon and hydrogen contents compared to petroleum diesel. This results in a reduction in mass energy content of about 10%, but a reduction in volumetric energy of only 5 – 7%.

Two properties that greatly influence the overall behavior and suitability of FAME as a diesel blendstock are: (1) the size distribution of the fatty acid (FA) chains and (2) the degree of unsaturation within these FA chains. Variations in biodiesel produced from different feedstocks can be explained largely by these two properties.

The two most common sets of regulatory standards for biodiesel blendstocks are ASTM D6751 in the U.S. and EN 14214 in Europe. Some of the specifications comprising these standards are directly related to the chemical composition of the FAME – such as viscosity, cetane number, cloud point, distillation, and iodine value. Other specifications relate to the purity of the FAME product, and address issues pertaining to production processes, transport, and storage – such as flash point, methanol content, metals content, sulfur level, acid number, and cold soak filterability.

Oxidative stability is an important property of biodiesel that is determined by both FAME chemical composition and by storage and handling conditions. Fuel oxidation is related to unsaturation within the

FA chain, and is especially promoted by multiple units of unsaturation. For this reason, the oxidative stability of camelina-based FAME and some algal-based FAME may be of concern.

Based upon an extensive review of published information, several important physical and chemical properties were compiled and compared for biodiesel fuels produced from 12 different vegetable oil and animal fat feedstocks. (At present, there is insufficient data in the literature to perform a similar analysis of biodiesel produced from algal feedstocks). Some properties are highly correlated, such as the low temperature properties of cloud point, pour point, and cold filter plugging point. Also, iodine value and cetane number are highly correlated. However, cetane number and cetane index are not highly correlated. It is concluded that cetane index not be used to characterize biodiesel.

For the set of biodiesel fuels investigated, a computed fuel property, called "average unsaturation," was highly correlated with several other properties, including viscosity, specific gravity, low temperature performance metrics, cetane number, and iodine value. An increase in average unsaturation leads to lower cetane number and poorer oxidation stability, but improved low temperature performance. Another computed property, "average chain length," was not well correlated with most other properties. This is somewhat surprising, since it is known from study of model compounds that chain length affects viscosity, cold flow properties, cetane number, and other fuel properties. To more clearly distinguish the independent effects of unsaturation and chain length (and other properties) in complex fuel mixtures requires use of sophisticated statistical analysis techniques.

Of the 12 biodiesel types investigated, coconut-derived FAME is unusual with respect to viscosity, density, flash point, iodine value, and heating value. This stems from coconut oil's compositional profile, which is dominated by short FA chains (especially C_{12}) and very low unsaturation (< 10% total unsaturates). Because of these properties, the suitability of coconut-derived FAME as a diesel blendstock is somewhat questionable.

An increasingly recognized problem with some biodiesel fuels is their propensity to form insoluble precipitates upon storage at low temperature. In large part, this problem is believed to be due to the presence of trace impurities – particularly sterol glucosides and saturated monoglycerides. These same impurities impart favorable lubricity performance to biodiesel; thus efforts to eliminate them could have an unintentional consequence of worsening lubricity.

Due to the conflicting impacts of certain FAME compositional features upon different fuel properties, it is not possible to define a single composition that is optimum with respect to all important properties. However, useful formulation guidelines can be offered with respect to two critical biodiesel fuel properties: (1) low temperature performance and (2) oxidative stability. For good low temperature performance, biodiesel should have low concentrations of long-chain saturated FAME, and high concentrations of unsaturated FAME. For good oxidative stability, biodiesel should have high concentrations of saturated and mono-unsaturated FAME, but low concentrations of multi-unsaturated FAME.

7.3   Emissions

Using a larger and more robust database than in the previous AVFL-17 study, the effects of biodiesel usage upon emissions were examined in both HD and LD engines/vehicles. These results generally confirmed earlier findings that increased B-level in HD engine applications decrease HC, CO, and PM emissions substantially, but slightly increase NOx. Results from HD chassis testing are similar, though not identical. Results from LD testing are more variable and quite different, showing small increases in CO, PM and NOx with increasing B-level.

The largest number of emission test results originate from use of B20 blends. Different data sorting methods were used to inspect these B20 results and investigate the effects of biodiesel feedstock, base fuel type, engine model year, and test cycle. The high degree of variability prevents firm conclusions from being made. More sophisticated data analysis techniques (and perhaps a larger dataset) would be required to discern these subtle effects.

The reported impacts of biodiesel upon aldehyde emissions are very inconsistent. Numerous examples of both aldehyde increases and decreases with changes in B-level are given in the literature. Generally, formaldehyde and acetaldehyde are the dominant emission species, although there are several reports where others – such as acrolein, proprionaldehyde, crotonaldehyde, benzaldehyde, and others – are significant contributors to the total aldehyde emissions.

Acrolein is an aldehyde of particular interest, since it is classified by EPA as a mobile source air toxic (MSAT), along with formaldehyde and acetaldehyde. The available data regarding impacts of biodiesel upon acrolein emissions is very sparse and uncertain. Acrolein is somewhat difficult to quantify because of its reactive nature. Also, some analytical methods commonly used to measure a variety of individual carbonyl compounds derivatives may not be able to reliably quantify acrolein in all situations.

The beneficial impact of biodiesel in reducing PM emissions is largely a consequence of fewer accumulation mode particles. Under some conditions, the number of smaller, nucleation mode particles has been found to increase with use of biodiesel. These so-called nanoparticles likely arise from condensation of unburned fuel or fuel impurities, and are expected to be readily removed by a diesel particulate emissions after-treatment system.

The amount of information available regarding PAH emissions is very limited. Although no firm conclusions can be made, it appears that use of biodiesel reduces or has no effect on PAH emissions. As the magnitude of these effects is rather small, they are unlikely to be significant when using low concentration biodiesel blends, such as B20.

The effects of biodiesel usage upon NOx emissions are not consistent across all engine types, operating modes, fuel compositions, and other parameters. Improved understanding of the so-called "NOx effect" has been gained in recent years. The increased speed of sound in biodiesel (compared to petroleum diesel) and bulk modulus of compressibility were once used to explain increased NOx emissions resulting from an inadvertent advance in fuel injection timing. This situation still exists in part of the legacy fleet, but is largely a problem of the past, having been eliminated by advancement in fuel injection technology.

In modern diesel engines, multiple inter-related factors contribute to the overall NOx effect. These include fuel compositional factors, fuel injection strategies, engine load conditions, and engine control/calibration approaches. There is considerable evidence that with all other factors being equal, NOx emissions increase with increasing fuel unsaturation and decreasing chain length.

Numerous approaches have been investigated to mitigate the NOx effect when using biodiesel blends. Fuel modifications that have demonstrated various degrees of success include reduction of aromatic content, addition of cetane improvers, addition of anti-oxidants, and blending with highly paraffinic stocks, such as F-T fuels or renewable diesel. Engine modifications for NOx control include retarded injection timing, split injection techniques, and use of EGR. An extreme example of these engine modifications results in operation known as low temperature combustion, which offers the possibility of simultaneous NOx and PM reductions.

With today's sophisticated electronically-controlled engines, it seems likely that the historic, adverse NOx effect from use of biodiesel can be eliminated. However, for this to succeed, a reliable fuel sensor must be utilized, so that the engine operation can be optimized for the particular fuel being used.

To meet increasingly stringent exhaust emissions standards, NOx after-treatment systems are now being introduced. Two general types are employed: one involving selective catalytic reduction (SCR) using ammonia as a reducing agent; the other involving NOx adsorber catalysts (NAC). Because these systems are still quite new, there is little information available about their in-use durability, or the impacts that biodiesel usage may have on them.

7.4   Life-Cycle Analyses and Carbon Footprint

The literature for life cycle assessments (LCA) of biofuels is growing rapidly in response to requirements that LCA approaches be used to support alternative fuel policies and GHG reduction strategies. There is great interest by all stakeholders in ensuring that each fuel (and fuel scenario) is being accurately and fairly represented.

In particular, the topic of indirect land use change (ILUC) has become the focus of much attention. Although there are numerous publications discussing the merits of ILUC, only a handful of studies have attempted to model the ILUC of biodiesel fuels. These show that the impacts can be quite substantial, with carbon payback periods reaching hundreds of years in some worst-case scenarios. Many regulators and policy-makers now agree that ILUC should not be overlooked. Consequently, both U.S. EPA and CARB include ILUC in their renewable fuel policies, while EU is still evaluating the best practices and methodologies by which to include ILUC.

The best practices for modeling ILUC are still under discussion by many groups. Assumptions of where the land use is occurring, how much land is affected, the soil and vegetation characteristics, and the time frame over which the land use changes occur have significant influence over the results. Approaches followed by CARB and EPA have undergone extensive peer review. Both of these approaches utilize and integrate several modeling tools in an attempt to accurately represent life-cycles and their emissions impacts. Also, both have opted to use a 30-year time horizon and a zero % discount rate.

Other influences of feedstock type (rapeseed, soy, etc.) and fuel type (biodiesel and renewable diesel) have been investigated. Excluding ILUC, there appear to be slight differences between feedstock type, with waste feedstocks (tallow and yellow grease) giving more favorable carbon intensity (CI) values than non-waste feedstocks, such as soy, rapeseed, and palm. Utilizing waste materials gives lower GHG impacts because cultivation activities -- including land use changes -- are not attributed to these materials. Also, feedstocks are influenced by regional agricultural practices, and utilizing local feedstocks reduces the impact of transportation distances, which can lessen the final CI impact.

LCA studies of the two most common biodiesel feedstocks, soy and rapeseed do not show consistent CI differences. LCA studies of "next generation" feedstocks such as jatropha and algae are increasing, but there are still too few of these to draw any firm conclusions. Similarly, no significant differences are seen in CI results from biodiesel compared to renewable diesel, though directionally, renewable diesel appears to be slightly more favorable. To reliably quantify such subtle effects would require additional, carefully matched modeling studies, and more sophisticated data analysis techniques.

A consensus has not yet been reached on other significant LCA assumptions, such as co-product allocation or N2O conversion ratios, both of which are also influential for ILUC effects. N2O emissions may be compounded for ILUC effects, both when new land is converted, and when an intensification of growth on existing land occurs through the addition of fertilizers. Since the global warming potential

(GWP) of N2O is very high, small changes in emissions can have large effects on CI, particularly if these effects are compounded over time. Because the input assumptions of each study vary significantly, direct comparison of final CI values should be done with extreme caution.

7.5   Regional Fuel Specifications and Quality

Many countries have now adopted standard specifications for biodiesel fuel (B100). Most of these standards are patterned after those established in the U.S. (ASTM D6751) and Europe (EN 14214). These standards are evolving to address new concerns about fuel quality and performance, and to accommodate introduction of improved analytical test methods.

Surveys of in-use biodiesel fuel quality have been conducted in the past, and have revealed some concerns about blending accuracy and adherence to fuel specifications. More recent surveys have shown improved quality. It may be advisable to conduct additional in-use fuel quality surveys now, since significant changes in fuel specifications (addition of Rancimat oxidative stability test and low temperature filtration test) and QA/QC practices (expansion of the BQ-9000 Process) have occurred recently.

8.   INFORMATION GAPS AND RECOMMENDATIONS FOR FURTHER WORK

1. Although the dominant U.S. biodiesel feedstock today is soybean oil, there is considerable interest in developing other vegetable oil feedstocks, especially camelina, canola, and corn. FAME produced from corn oil currently contributes a negligible amount to the total biodiesel fuel used in the U.S. However, EPA's RFS2 Regulatory Impact Analysis states that by the year 2020, corn-derived FAME will be the largest single source of biodiesel, contributing about 40% of the total. If this is to occur, major changes in the biodiesel industry will be required, including expansion of infrastructure for production, transport, and blending of biodiesel.

   Recommendation: Monitoring of technical and regulatory activities related to development of new biodiesel feedstocks should continue – particularly corn oil feedstocks. Once sufficient corn-derived biodiesel is available for use, research should be considered to investigate the properties and performance of this material, and to assess its suitability as a diesel blendstock. Similarly, camelina-derived FAME should be investigated for its suitability.

2. Interest in utilizing algal lipids as biodiesel feedstocks continues to grow. Much R&D has been focused on identifying preferred algal species and growth conditions for maximal lipid production, harvesting and de-watering approaches, and conversion technologies for production of FAME (and renewable diesel). Yet, there is very little information about the compositional profiles of different algal species, or about the fuel properties likely to result from use of one species compared to another. In particular, the high level of unsaturation in some algal-based biodiesel could be a concern with respect to oxidative stability.

   Recommendation: Monitoring of R&D activities investigating use of algal lipids as biodiesel feedstocks should continue. In the future, it may be important to conduct experimental work focused on characterizing the compositional profiles, fuel properties, and in-use performance of biodiesel fuels produced from algal sources.

3. The beneficial impacts of biodiesel usage on emissions from HD engines are reasonably well understood for the criteria pollutants of HC, CO, and total PM. Impacts on NOx emissions are smaller, and less consistent. Factors contributing to the "NOx effect" of biodiesel are much better understood now than a few years ago, including the impacts of fuel composition, fuel injection

strategies, engine load, and engine control/calibration approaches. Effective NOx mitigation has been demonstrated using EGR, retarded injection timing, and other measures. Also, after-treatment systems utilizing selective catalytic reduction (SCR) or NOx adsorber catalyst (NAC) systems are now beginning to appear in commercial applications.

Recommendation: The performance and durability of advanced NOx after-treatment emissions control systems now being commercially introduced should be monitored. Experimental work should be considered to better define the impacts of biodiesel usage upon these NOx control systems. At the same time, it may be of interest to investigate the impacts of biodiesel use on the performance of diesel PM trap after-treatment systems, and to confirm that such systems are effective in removing nanoparticles that arise from condensation of unburned fuel.

4. Compared to the criteria emissions (HC, CO, PM, and NOx), relatively little is known about the impacts of biodiesel upon mobile source air toxics (MSATs). Of greatest concern are the aldehydes: formaldehyde, acetaldehyde, and acrolein – all of which are classified as MSATs. The information currently available regarding aldehyde emissions impacts of biodiesel usage is variable and inconsistent.

   Recommendation: Carefully controlled laboratory experimental test programs should be considered to investigate the effects of biodiesel type and purity upon aldehyde emissions from one or more modern diesel engines – model year 2007 or later. Special efforts may be required to collect and reliably measure acrolein, which historically has been difficult to quantify.

5. The number of LCA studies for biodiesel is expanding rapidly, both in the U.S. and elsewhere. While most studies have focused on soy- and rapeseed-derived biodiesel, other feedstocks are beginning to receive increased attention. Carbon intensity (CI) results computed from different LCA modeling studies continue to be highly variable, depending upon numerous critical input assumptions. Among the most influential assumptions are those pertaining to co-product allocation and land use change.

   Recommendation: Monitoring of technical and policy developments in the area of biofuels LCA should continue. A global workshop hosted by a neutral party should be considered to objectively assess modeling assumptions and approaches. Also, specific R&D projects should be considered to ensure that reasonable model input assumptions are used for all fuels.

APPENDICES

Appendix I. 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 year
BHP	Brake horsepower
BMEP	Brake mean effective pressure
BTDC	Before top dead center
BTL	Biomass-to-liquids
BTU	British thermal unit
CAA	Clean Air Act
CAD	Crank angle degree
CARB	California Air Resources Board
CCI	Calculated cetane index
CEN	European Committee for Standardization
CFI	Cold flow improver
CFPP	Cold filter plugging point
CFR	Code of Federal Regulations
CI	Compression ignition; also carbon intensity; also cetane index
CIDI	Compression ignition direct injection
CN	Cetane number
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Cloud point
CRC	Coordinating Research Council
DARPA	Defense Advanced Research Projects Agency
DI	Direct injection
DOC	Diesel oxidation catalyst
DOE	U.S. Department of Energy
DPNR	Diesel particulate and NOx reduction
DPF	Diesel particulate filter
EBAMM	ERG Biofuel Analysis Meta-Model
ECU	Engine control unit
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EMA	Engine Manufacturers' Association
EN	European Norm
EPA	U.S. Environmental Protection Agency
EROI	Energy return on investment (also called ER)
ESC	European stationary cycle
ETC	European transient cycle
EU	European Union
EUP	Eutrophication potential

FAEE	Fatty acid ethyl ester
FAME	Fatty acid methyl ester
FASOM	Forest and Agricultural Sector Optimization Model
FCC	Fluid catalytic cracking
FFA	Free fatty acid
F-T	Fischer-Tropsch
FTD	Fischer Tropsch diesel
FTP	Federal test procedure
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GTL	Gas-to-liquids
GWP	Global warming potential
HC	Hydrocarbons
HCCI	Homogeneous charge compression ignition
HDDV	Heavy-duty diesel vehicle
HEV	Hybrid electric vehicle
HHV	Higher heating value
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IDI	Indirect injection
IMEP	Indicated mean effective pressure
IPCC	Intergovernmental Panel on Climate Change
IV	Iodine value
LAD	Low aromatic diesel fuel
LCA	Life-cycle assessment
LCFS	Low carbon fuel standard
LDDV	Light-duty diesel vehicle
LHV	Lower heating value
LTC	Low temperature combustion
LTFT	Low temperature flow test
LSD	Low sulfur diesel
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
NAC	NOx adsorber catalyst
NBB	National Biodiesel Board
NCWM	National Conference on Weights and Measures
NCRD	Non co-processed renewable diesel
NEDC	New European driving cycle
NERD	Non-ester renewable diesel
NMHC	Non-methane hydrocarbons
NO	Nitric oxide
NO_2	Nitrogen dioxide

NOx	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_3	Ozone
OBD	On-board diagnostics
OEM	Original equipment manufacturer
OSI	Oxidative stability index
PAH	Polycyclic aromatic hydrocarbon
PM	Particulate matter
PM_{10}	PM with diameter $\leq$ 10 μm
$PM_{2.5}$	PM with diameter $\leq$ 2.5 μm
PME	Palm oil methyl ester
POCP	Photochemical ozone creation potential
PP	Pour point
RFS	Renewable fuel standard
RME	Rapeseed methyl ester
S	Sulfur
SAE	Society of Automotive Engineers International
SCR	Selective catalytic reduction
SG	Sterol glucoside
SME	Soy methyl ester
SI	Spark ignition
SOI	Start of injection
SOx	Oxides of sulfur
SVO	Straight vegetable oil
TAN	Total acid number
TDC	Top dead center
TDP	Thermal de-polymerization
THC	Total hydrocarbons
TTW	Tank-to-wheels
UDDS	Urban dynamometer driving schedule
ULSD	Ultra-low sulfur diesel fuel (max. of 15 ppmS)
VGT	Variable geometry turbocharger
VOC	Volatile organic compound
WAP	Wax appearance point
WTE	Waste-to-energy
WTT	Well-to-tank
WTW	Well-to-wheels
WVO	Waste vegetable oil

Appendix II. Glossary of Fuel Terms

1st 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).
2nd 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.
B-level	Shorthand term used to indicate the concentration of biodiesel included in a fuel blend. For example, B20 has a B-level of 20.
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 and the popular press.
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 animal fats and vegetable oils.
Fischer-Tropsch (F-T) Diesel	Diesel fuel produced via gasification of organic feedstocks, followed by Fischer-Tropsch catalytic 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 III. Table of Conversion Factors

Land Area	1 Acre = 0.405 Hectares 1 Hectare = 10,000 m^2
Pressure	1 Atmosphere = 1.013 Bar = 14.7 psi 1 Atmosphere = 0.1013 MPa 1 MPa = 9.87 Atmospheres = 145 psi
Mass	1 Metric Tonne = 1000 kg = 2205 lb 1 U.S. Ton = .908 Metric Tonnes 1 lb. = 0.454 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 = 3.97 BTU 1 BTU = 1.055 kJ = 0.252 kcal 1 BTU/lb. = 2.326 kJ/kg = 0.555 kcal/kg 1 BTU/Gal. = 0.279 kJ/L 1 Quad = 10^{15} BTU = 1.055 Exajoules (EJ) 1.0 EJ = 1 × 10^{18} joules
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)	1.0 Gal Gasoline = 115,000 BTU = 121 MJ 1.0 Gal Petroleum Diesel = 130,500 BTU = 137 MJ 1.0 Gal Biodiesel = 122,000 BTU = 128 MJ 1.0 Gal Ethanol = 75,700 BTU = 80 MJ
Vehicle Exhaust Emissions Rates	1.0 g/bhp-hr = 1.341 g/KW-hr 1.0 g/mile = 0.621 g/km
Other (Approximate)	1 Metric Tonne Biodiesel = 300 U.S. Gallon 100 U.S. Gal. Biodiesel/acre = 0.33 tonnes/acre

Appendix IV. Fatty Acid Compositional Profiles of Biodiesel (FAME) from Fats and Oils

1. Camelina

2. Canola

3. Coconut

4. Corn

5. Jatropha

6. Palm

7. Rapeseed

8. Safflower

9. Soybean

10. Sunflower

11. Tallow

12. Yellow Grease

Appendix IV. Fatty Acid Compositional Profiles of Biodiesel (FAME) from Fats and Oils

1. Biodiesel from Camelina *									
Fatty Acid		[335]	[336]	[337]	[338]	[339]	[340]	Results	
Common Name	Abbrev.							mean	Dev
Capriotic	6:0								
Caprylic	8:0								
Capric	10:0				3.5				
Lauric	12:0				0.4			0.4	
Tridecylic	13:0								
Myristic	14:0				5.2	0.1		2.7	3.6
Myristoleic	14:1								
Pentadanoic	15:0								
Pentadecenoic	15:1								
Palmitic	16:0	5.0	5.4	5.0	8.7	6.8	5.4	6.1	1.5
Palmitoleic	16:1								
Hexadecadienoic	16:2								
Hexadecatrienoic	16:3								
Heptadecanoic	17:0								
Heptadecenoic	17:1								
Stearic	18:0	2.2	2.6	3.0	3.5	2.7	2.6	2.8	0.4
Oleic	18:1	17.7	14.3	14.0	20.6	19.7	14.3	16.8	3.0
Linoleic	18:2	18.0	14.3	16.0	5.1	19.6	2.9	17.0	2.3
Linolenic	18:3	37.9	38.4	36.0	30.5	32.6	38.4	35.6	3.4
Stearidonic	18:4								
Arachidic	20:0	1.4	0.3	1.0	3.8	1.5	0.3	1.4	1.3
Gondoic	20:1	9.8	16.8	15.0	15.7	12.4	16.8	14.4	2.8
Eicosadiensic	20:2	1.6				1.3		1.5	0.2
Eicosatrienoic	20:3					0.8		0.8	
Eicosatetraenoic	20:4								
Eicosapentaenoic	20:5								
Behenic	22:0	0.4	1.4	1.0		0.2	1.4	0.9	0.6
Erucic	22:1	4.5	2.9	3.0		2.3	2.9	3.1	0.8
Docosatetraenoic	22:4								
Docosapentaenoic	22:5								
Docosahexaenoic	22:6								
Lignoceric	24:0	0.3		1.0				0.7	0.5
Nervonic	24:1	0.2						0.2	
Other/Unknown		1.0						1.0	
Total		99.0	96.4	95.0	97.0	100.0	85.0	104.1	

= not included in mean and S.D.

* Literature references identified in [square brackets].

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Appendix IV Compositional Profiles (cont.)

Fatty Acid		[335]	[341]	[93]	[102]	[342]	[187]	[112]	[343]	[344]	[345]	[339]	[346]	[347]	[348]	Results	
2. Biodiesel from Canola *																	
Common Name	Abbrev.															mean	Dev
Capriotic	6:0																
Caprylic	8:0									0.0				0.0		0.0	0.0
Capric	10:0			0.1						0.0				0.0		0.0	0.1
Lauric	12:0			0.0						0.0				0.0		0.0	0.0
Tridecylic	13:0																
Myristic	14:0		0.1	0.0		0.1			0.1	0.0				0.0		0.0	0.0
Myristoleic	14:1			0.0												0.0	
Pentadanoic	15:0																
Pentadecenoic	15:1																
Palmitic	16:0	3.8	4.6	3.8	4.6	5.5	5.1	4.6	5.1	3.9	3.9	4.6	1.2	4.2	3.9	4.2	1.0
Palmitoleic	16:1	0.3	0.3	0.2		1.1		0.2	0.3		0.2	0.2		0.0	0.3	0.3	0.3
Hexadecadienoic	16:2																
Hexadecatrienoic	16:3																
Heptadecanoic	17:0								0.1							0.1	
Heptadecenoic	17:1								0.1							0.1	
Stearic	18:0	1.9	1.7	1.7	2.0	2.2	1.8	2.1	1.8	3.1	1.9	2.1	2.5	1.7	1.6	2.0	0.4
Oleic	18:1	63.9	60.6	59.6	60.0	55.0	58.4	64.3	58.4	60.2	64.1	64.3	61.4	56.8	58.4	60.4	2.9
Linoleic	18:2	19.0	20.4	18.5	21.7	24.0	23.4	20.2	23.4	21.1	18.7	20.2	22.3	21.7	22.2	21.2	1.8
Linolenic	18:3	9.7	9.2	8.8	7.9	8.8	8.4	7.6	8.4	11.1	9.2	7.6	11.5	15.7	9.9	9.6	2.1
Stearidonic	18:4																
Arachidic	20:0	0.6	0.6	1.3	0.8	0.7		0.7	0.6		0.6	0.7		0.0	0.8	0.7	0.3
Gondoic	20:1		1.3		1.5	1.4			1.2					0.0	1.8	1.5	0.2
Eicosadiensic	20:2		0.1													0.1	
Eicosatrienoic	20:3																
Eicosatetraenoic	20:4																
Eicosapentaenoic	20:5																
Behenic	22:0	0.4	0.3	0.3	0.3	0.5		0.3	0.4		0.2	0.3		0.0	0.3	0.3	0.1
Erucic	22:1		0.3		0.8	0.4			0.3	0.5				0.0	0.8	0.5	0.2
Docosatetraenoic	22:4																
Docosapentaenoic	22:5																
Docosahexaenoic	22:6																
Lignoceric	24:0	0.2				0.3			0.1					0.0		0.2	0.1
Nervonic	24:1	0.2														0.2	
Other/Unknown				2.2												2.2	
Total		100.0	99.4	94.3	99.6	100.0	97.0	100.0	100.0	99.9	98.8	100.0	98.9	100.1	100.0	101.2	

= not included in mean and S.D.

* Literature references identified in [square brackets].

Fatty Acid Common Name	Abbrev.	[335]	[212]	[349]	[181]	[350]	[351]	[352]	[344].	[345]	[353]	[347]	[354]	[355]	[356]	Results mean	Dev
3. Biodiesel from Coconut *																	
Capriotic	6:0		0.4	0.4						0.5		1.1				0.6	0.3
Caprylic	8:0	6.3	7.0	5.8	6.0	8.3		7.1	8.3	8.0		9.2	8.9	3.5	3.4	6.8	1.9
Capric	10:0	6.0	6.0	5.1	4.9	6.0			6.0	6.4		6.4	6.2	3.5	3.2	5.4	1.1
Lauric	12:0	49.2	47.5	44.6	52.4	46.7	54.4	54.1	46.7	48.5		48.7	48.8	46.3	32.7	47.7	5.4
Tridecylic	13:0																
Myristic	14:0	18.5	19.1	19.1	16.9	18.3	21.4	17.4	18.3	17.6		17.0	20.0	15.8	18.4	18.5	1.3
Myristoleic	14:1																
Pentadanoic	15:0																
Pentadecenoic	15:1																
Palmitic	16:0	9.1	9.8	10.0	8.6	9.2	10.6	6.1	9.2	8.4	5.0	7.7	7.8	9.0	13.1	9.1	1.7
Palmitoleic	16:1						0.2					0.0				0.1	0.2
Hexadecadienoic	16:2																
Hexadecatrienoic	16:3																
Heptadecanoic	17:0																
Heptadecenoic	17:1																
Stearic	18:0	2.7	3.8	3.6	2.3	2.9	1.7	1.6	2.9	2.5	3.0	2.2	3.1	15.1	3.6	2.7	0.7
Oleic	18:1	6.5	5.9	8.8	6.5	6.9	6.4	5.1	6.9	6.5	6.0	5.4	4.4	6.1	12.9	6.8	2.1
Linoleic	18:2	1.7	0.4	2.7	1.4	1.7	5.3	1.3	1.7	1.5		2.2	0.8		4.4	2.1	1.4
Linolenic	18:3		0.1		0.3					0.0		0.0				0.1	0.1
Stearidonic	18:4																
Arachidic	20:0									0.1		0.0				0.1	0.1
Gondoic	20:1											0.0				0.0	
Eicosadiensic	20:2																
Eicosatrienoic	20:3																
Eicosatetraenoic	20:4																
Eicosapentaenoic	20:5																
Behenic	22:0																
Erucic	22:1								0.0			0.0				0.0	0.0
Docosatetraenoic	22:4											0.0				0.0	
Docosapentaenoic	22:5																
Docosahexaenoic	22:6																
Lignoceric	24:0											0.0				0.0	
Nervonic	24:1				1.0											1.0	
Other/Unknown											65.0						
Total		100.0	100.0	100.0	100.3	100.0	100.0	92.7	100.0	100.0	14.0	99.9				101.1	

= not included in mean and S.D.

* Literature references identified in [square brackets].

| Fatty Acid | | [335] | [215] | [55] | [102] | [350] | [109] | [345] | [353] | [357] | [358] | [359] | [360] | Results | |
Common Name	Abbrev.													mean	Dev
4. Biodiesel from Corn *															
Capriotic	6:0														
Caprylic	8:0														
Capric	10:0														
Lauric	12:0						0.0							0.0	
Tridecylic	13:0														
Myristic	14:0						0.0						0.0	0.0	0.0
Myristoleic	14:1														
Pentadanoic	15:0														
Pentadecenoic	15:1														
Palmitic	16:0	12.1	11.4	12.4	12.3	11.7	6.5	12.2	6.0	12.0	11.7	11.8	12.0	11.5	1.7
Palmitoleic	16:1	0.1		0.2			0.6	0.1				0.0		0.2	0.2
Hexadecadienoic	16:2														
Hexadecatrienoic	16:3														
Heptadecanoic	17:0														
Heptadecenoic	17:1	0.1												0.1	
Stearic	18:0	1.8	1.3	1.9	2.0	1.9	1.4	2.2	2.0	2.0	1.9	2.0	2.0	1.9	0.3
Oleic	18:1	27.2	27.1	31.1	29.8	25.2	25.2	27.5	44.0	25.0	25.2	24.8	25.0	26.6	2.2
Linoleic	18:2	56.2	60.2	53.5	54.7	60.6	61.3	57.0	48.0	60.0	60.6	61.3	60.6	58.7	2.8
Linolenic	18:3	1.3		0.9	0.5	0.5	0.1	0.9		1.0	0.5	0.0		0.6	0.4
Stearidonic	18:4														
Arachidic	20:0	0.4			0.6		0.1	0.1			0.2			0.3	0.2
Gondoic	20:1						0.1							0.1	
Eicosadiensic	20:2														
Eicosatrienoic	20:3														
Eicosatetraenoic	20:4														
Eicosapentaenoic	20:5														
Behenic	22:0	0.2					0.0						0.0	0.1	0.1
Erucic	22:1						0.1						0.0	0.1	0.1
Docosatetraenoic	22:4														
Docosapentaenoic	22:5														
Docosahexaenoic	22:6														
Lignoceric	24:0						0.1						0.0	0.1	0.1
Nervonic	24:1						0.0							0.0	
Other/Unknown												0.3		0.3	
Total		99.4	100.0	100.0	100.0	99.8	95.5	100.0	100.0	100.0	100.0	99.9	99.6	100.2	

       = not included in mean and S.D.

       = 18:1 and 18:2 reversed from literature values

* Literature references identified in [square brackets].

5. Biodiesel from Jatropha *

| Fatty Acid | | [158] | [335] | [239] | [184] | [361] | [362] | [25] | [363] | [363] | [364] | [365] | [351] | [366] | [367] | [368] | [369] | [370] | [371] | [372] | [373] | [374] | [375] | Results | |
Common Name	Abbrev.																							mean	Dev
Capriotic	6:0																								
Caprylic	8:0																								
Capric	10:0																								
Lauric	12:0	0.0				5.9							0.1		0.3									0.1	0.2
Tridecylic	13:0																								
Myristic	14:0	0.0				2.7			0.1	0.1		0.4	0.1							0.5	1.4		0.1	0.3	0.5
Myristoleic	14:1																								
Pentadanoic	15:0																								
Pentadecenoic	15:1																								
Palmitic	16:0	12.6	12.7	15.7	16.0	13.5	18.2	13.5	15.1	13.6	14.2	16.0	15.0	14.2	13.4	18.5	19.5	12.8	11.3	11.8	15.6	12.2	15.3	14.9	2.1
Palmitoleic	16:1	0.8	0.7					0.8	0.9	0.8	1.4	2.3	1.1	1.4	0.9					0.5			0.9	1.0	0.5
Hexadecadienoic	16:2																								
Hexadecatrienoic	16:3																								
Heptadecanoic	17:0																							0.1	0.1
Heptadecenoic	17:1																								
Stearic	18:0	5.9	5.5	6.9	6.5	6.1	5.1	7.2	7.1	7.4	6.9	6.5	3.9	6.9	5.4	2.3	6.8	7.3	17.0	2.5	9.7	16.8	6.6	6.1	1.7
Oleic	18:1	35.8	39.1	43.1	43.5	21.8	28.5	47.3	44.7	34.3	43.1	42.8	32.5	43.1	45.8	49.0	41.3	44.8	12.8	45.6	40.8	13.0	41.0	40.4	6.7
Linoleic	18:2	28.8	41.6	34.3	34.4	47.4	48.2	30.7	31.4	43.2	34.4	33.7	47.4	34.3	32.3	29.7	31.4	34.0	47.3	39.0	32.1	49.8	35.3	36.2	6.1
Linolenic	18:3	0.2	0.2					0.3	0.2	0.2		0.8								0.2			0.3	0.3	0.2
Stearidonic	18:4																								
Arachidic	20:0	0.2	0.2					0.3	0.2	0.2		0.2							4.7	0.1	0.4	5.0	0.2	0.2	0.1
Gondoic	20:1	0.1										0.1							1.8	0.1		2.0	0.1	0.1	0.0
Eicosadiensic	20:2																								
Eicosatrienoic	20:3																								
Eicosatetraenoic	20:4																								
Eicosapentaenoic	20:5																								
Behenic	22:0	0.1							0.2	0.3									0.6			0.6		0.2	0.1
Erucic	22:1	0.0																					0.1	0.1	0.1
Docosatetraenoic	22:4																								
Docosapentaenoic	22:5																								
Docosahexaenoic	22:6																								
Lignoceric	24:0	5.1																	44.0				0.1	2.6	3.5
Nervonic	24:1	0.1																						0.1	
Other/Unknown						2.7			0.1	0.1					1.9			1.1						1.2	1.1
Total		89.7	100.0	100.0	100.4	97.4	100.0	100.0	99.9	100.1	100.0	102.7	100.0	99.9	98.1	99.5	99.0	98.9	139.5	100.2	100.0	99.3	100.1	102.7	

■ = not included in mean and S.D.

* Literature references identified in [square brackets].

Fatty Acid Common Name	Abbrev.	[376]	[158]	[150]	[335]	[215]	[55]	[93]	[90]	[377]	[212]	[349]	[181]	[89]	[110]	[112]	[378]
6. Biodiesel from Palm (Page 1 of 2) *																	
Capriotic	6:0																
Caprylic	8:0			2.3								3.8	.				
Capric	10:0			1.8				0.0				3.7					
Lauric	12:0	0.4	0.2	21.8	0.2	0.5		0.3	0.2		0.3	48.4	0.3			0.3	1.3
Tridecylic	13:0																
Myristic	14:0	1.1	1.1	6.4	0.5	1.6		1.0	1.0		1.1	17.4	1.1	0.6	1.0	1.1	1.1
Myristoleic	14:1								0.0								
Pentadanoic	15:0																
Pentadecenoic	15:1																
Palmitic	16:0	42.2	43.0	24.5	43.4	49.8	43.9	40.0	44.3	35.0	44.1	9.1	48.8	47.2	40.1	41.9	42.1
Palmitoleic	16:1		0.2		0.1		0.1	0.2	0.2		0.2			0.0		0.2	0.2
Hexadecadienoic	16:2																
Hexadecatrienoic	16:3																
Heptadecanoic	17:0								0.1								
Heptadecenoic	17:1																
Stearic	18:0	3.0	4.7	3.2	4.6	2.9	4.3	4.1	4.3	7.0	4.5	2.7	1.7	3.0	4.1	4.6	3.9
Oleic	18:1	43.0	40.1	31.9	41.9	38.6	40.9	41.5	39.7	44.0	40.1	12.6	38.4	40.8	43.0	41.2	43.0
Linoleic	18:2	10.3	9.5	7.2	8.6	6.6	10.6	10.6	9.6	14.0	9.1	2.4	9.1	8.2	11.0	10.3	7.0
Linolenic	18:3		0.2	0.1	0.3		0.2	0.4	0.2		0.6		0.5	0.2	0.2	0.1	0.5
Stearidonic	18:4																
Arachidic	20:0		0.4	0.2	0.3			0.1	0.4						0.3	0.3	0.1
Gondoic	20:1		0.2						0.1								
Eicosadiensic	20:2								0.0								
Eicosatrienoic	20:3																
Eicosatetraenoic	20:4																
Eicosapentaenoic	20:5																
Behenic	22:0		0.0		0.1			0.0									
Erucic	22:1		0.0						0.0								
Docosatetraenoic	22:4																
Docosapentaenoic	22:5																
Docosahexaenoic	22:6																
Lignoceric	24:0		0.0						0.0								
Nervonic	24:1		0.0						0.0								
Other/Unknown			0.4					0.4					0.1				
Total		100.0	99.6	99.5	100.0	100.0	100.0	98.2	100.1	100.0	100.0	100.0	99.9	100.0	99.8	100.0	99.1

██ = not included in mean and S.D.

* Literature references identified in [square brackets].

6. Biodiesel from Palm (Page 2 of 2) *													
[350]	[351]	[352]	[366]	[85]	[109]	[344]	[345]	[339]	[347]	[358]	[359]	Results	
												mean	Dev
					0.1				0.0			0.8	1.3
					0.1				0.0			0.5	0.9
0.1	0.4				0.1	0.9	0.3	0.3	0.0	0.1		0.3	0.3
1.0	1.2	2.5			0.7	1.3	1.1	1.1	0.0	1.0		1.1	0.5
												0.0	
42.8	42.4	40.8	40.3	39.5	36.7	43.9	45.1	41.9	40.6	42.8	42.6	42.5	3.2
	0.3				0.1		0.1	0.2	0.0		0.3	0.2	0.1
												0.1	
4.5	3.3	3.6	2.7	4.1	6.6	4.9	4.7	4.6	5.1	4.5	4.4	4.2	1.1
40.5	47.0	45.2	43.4	43.2	46.1	39.0	38.5	41.2	42.8	40.5	40.5	41.3	2.9
10.1	5.3	7.9	12.7	10.6	8.6	9.5	9.4	10.3	11.0	10.1	10.1	9.5	1.8
0.2					0.2	0.3	0.3	0.3	0.1	0.5	0.2	0.2	0.3	0.1
					0.4		0.2	0.3	0.0			0.3	0.1
					0.2				0.0			0.1	0.1
												0.0	
					0.1				0.0			0.0	0.1
					0.0	0.0			0.0			0.0	0.0
					0.1				0.0			0.0	0.1
					0.0							0.0	0.0
				2.4							1.1	0.9	0.9
99.2	100.0	100.0	99.1	97.6	100.0	100.0	99.7	100.0	100.0	99.2	98.1	101.2	

* Literature references identified in [square brackets].

7. Biodiesel from Rapeseed *

Fatty Acid Common Name	Abbrev.	[376]	[111]	[158]	[379]	[215]	[55]	[90]	[186]	[380]	[212]	[336]	[110]	[350]	[352]	[381]	[85]	[109]	[344]	[345]	[353]	[359]	[360]	[382]	Results mean	Dev
Capriotic	6:0																									
Caprylic	8:0																		0.0							
Capric	10:0													0.6					0.0						0.6	
Lauric	12:0		0.3	0.0				0.0										0.0	0.0						0.1	0.1
Tridecylic	13:0																									
Myristic	14:0			0.1	0.1			0.0		0.1			0.1		0.1			0.0	0.0	0.1			0.0	0.0	0.0	0.0
Myristoleic	14:1																									
Pentadanoic	15:0																									
Pentadecenoic	15:1																									
Palmitic	16:0	4.2	5.4	4.6	6.1	5.2	2.1	4.4	2.8	10.5	4.3	6.1	4.4	3.5	5.1	3.5	4.3	4.9	2.7	2.8	3.5	3.5	3.0	3.5	4.2	1.1
Palmitoleic	16:1			0.3	0.1			0.3	0.2		0.1							0.0		0.2	0.1	0.0			0.1	0.1
Hexadecadienoic	16:2																									
Hexadecatrienoic	16:3																									
Heptadecanoic	17:0							0.1																	0.1	
Heptadecenoic	17:1				0.0																				0.0	
Stearic	18:0	1.7	2.9	1.8	3.6	1.4	1.7	1.6	0.9	3.8	1.9	2.3	1.7	0.9	2.1	0.9	1.9	1.6	2.8	1.3	0.9	0.9	1.0	0.9	1.6	0.7
Oleic	18:1	63.0	48.2	60.7	61.0	66.0	65.2	60.7	12.6	23.2	59.7	56.0	62.4	64.4	57.9	64.4	61.5	33.0	21.9	21.8	54.1	64.1	64.0	64.4	59.5	7.8
Linoleic	18:2	19.7	24.8	19.1	27.9	18.9	21.2	19.6	12.1	48.9	21.7	24.2	19.7	22.3	24.7	22.3	20.6	20.4	13.1	14.6	22.3	22.3	22.0	22.3	21.5	2.8
Linolenic	18:3	11.4		8.3	0.1	5.6	9.5	10.2	8.0	1.2	9.4	6.5	9.5	8.2	7.9	8.2	8.3	7.9	8.6	7.3		8.2	8.0	8.2	8.4	1.3
Stearidonic	18:4																									
Arachidic	20:0		0.2	0.6	0.3	1.9		0.6	0.8			0.3	0.6		0.2			0.0		0.7			0.0	0.0	0.4	0.5
Gondoic	20:1			1.4	0.2			1.4	7.4			1.5	0.3	1.3	1.0			9.3		34.8					2.1	3.0
Eicosadiensic	20:2							0.1																	0.1	
Eicosatrienoic	20:3																									
Eicosatetraenoic	20:4																									
Eicosapentaenoic	20:5																									
Behenic	22:0			0.3	0.7	1.0		0.4	0.7		0.4	0.4			0.2			0.0		0.4			0.0	0.0	0.3	0.3
Erucic	22:1		0.6	0.3					49.8		0.6	1.5			0.2			23.0	50.9				0.0		0.5	0.5
Docosatetraenoic	22:4																									
Docosapentaenoic	22:5																									
Docosahexaenoic	22:6																									
Lignoceric	24:0			0.1				0.1										0.0					0.0	0.0	0.0	0.1
Nervonic	24:1			0.1				0.2	0.9									0.0							0.1	0.1
Other/Unknown				0.4						12.2									3.4			9.1			4.3	4.4
Total		100.0	82.2	97.7	100.0	100.0	100.0	99.6	96.0	87.6	99.6	97.6	99.6	99.3	100.0	99.3	96.6	100.1	100.0	84.0	80.9	99.0	98.0	99.3	99.9	

= not included in mean and S.D.

= 18:1 18:2 reversed from literature values

* Literature references identified in [square brackets].

Fatty Acid		[350]	[381]	[85]	[344]	[345]	[353]	[383]	[360]	[382]	Results	
Common Name	Abbrev.										mean	Dev
8. Biodiesel from Safflower *												
Capriotic	6:0											
Caprylic	8:0				0.0						0.0	
Capric	10:0				0.0						0.0	
Lauric	12:0				0.0						0.0	
Tridecylic	13:0											
Myristic	14:0				0.1	0.1			0.0	0.0	0.1	0.1
Myristoleic	14:1											
Pentadanoic	15:0											
Pentadecenoic	15:1											
Palmitic	16:0	7.3	10.6	6.4	6.6	10.9	7.3	7.3	9.0	8.6	8.2	1.7
Palmitoleic	16:1					0.1	0.1				0.1	0.0
Hexadecadienoic	16:2											
Hexadecatrienoic	16:3											
Heptadecanoic	17:0											
Heptadecenoic	17:1											
Stearic	18:0	1.9	4.8	2.2	3.3	2.4	1.9	1.9	2.0	1.9	2.5	1.0
Oleic	18:1	13.6	22.5	13.9	14.4	13.1	13.5	13.6	12.0	11.6	14.2	3.2
Linoleic	18:2	77.2	52.3	76.0	75.5	77.7	77.0	77.2	78.0	77.9	74.3	8.3
Linolenic	18:3			0.2	0.1				0.0	0.0	0.1	0.1
Stearidonic	18:4											
Arachidic	20:0					0.2			0.0	0.0	0.1	0.1
Gondoic	20:1											
Eicosadiensic	20:2											
Eicosatrienoic	20:3											
Eicosatetraenoic	20:4											
Eicosapentaenoic	20:5											
Behenic	22:0								0.0	0.0	0.0	
Erucic	22:1				0.0				0.0		0.0	0.0
Docosatetraenoic	22:4											
Docosapentaenoic	22:5											
Docosahexaenoic	22:6											
Lignoceric	24:0								0.0	0.0	0.0	
Nervonic	24:1											
Other/Unknown				1.3		0.2					0.8	0.8
Total		100.0	90.2	98.7	100.0	104.5	99.8	100.0	101.0	100.0	99.5	

* Literature references identified in [square brackets].

9. Biodiesel from Soybean Oil (Page 1 of 2) *

Fatty Acid Common Name	Abbrev.	[244]	[376]	[384]	[190]	[159]	[335]	[189]	[215]	[55]	[93]	[90]	[129]	[385]	[102]	[380]	[377]	[212]	[89]	[110]	[112]	[185]
Capriotic	6:0																					
Caprylic	8:0																					
Capric	10:0										0.0											
Lauric	12:0							0.0			0.0	0.0	0.0	0.4								0.2
Tridecylic	13:0																					
Myristic	14:0		0.4	0.0	0.0			0.0			0.1	0.1	0.0	0.3		0.1				0.0	0.1	0.7
Myristoleic	14:1										0.0		0.0									
Pentadanoic	15:0																					
Pentadecenoic	15:1																					
Palmitic	16:0	11.2	14.0	10.8	14.1	8.8	9.4	12.0	11.7	7.1	10.8	10.4	16.3	10.9	10.3	5.3	14.0	10.5	11.0	11.0	10.5	15.3
Palmitoleic	16:1			0.0	0.7	0.1		0.0			0.2	0.2	0.1	0.0						0.0		0.8
Hexadecadienoic	16:2																					
Hexadecatrienoic	16:3																					
Heptadecanoic	17:0											0.1	0.0									8.9
Heptadecenoic	17:1																					
Stearic	18:0	4.5	4.7	3.5	5.2	4.6	4.1	3.9	4.0	3.4	4.5	4.2	6.0	4.1	4.0	2.5	4.0	3.8	4.2	4.3	4.1	3.9
Oleic	18:1	22.4	33.8	22.3	25.3	24.2	22.0	22.6	21.3	26.2	21.9	24.5	24.3	23.4	22.4	21.8	24.0	25.0	22.6	23.1	24.1	17.8
Linoleic	18:2	52.3	42.4	56.4	48.7	52.7	55.3	54.5	53.7	62.9	51.3	52.0	53.4	52.3	53.5	58.1	52.0	52.2	55.0	53.3	53.6	34.5
Linolenic	18:3	8.3	4.7	7.0	6.1	7.7	8.9	6.6	8.1	0.3	7.6	7.7	0.0	0.2	7.8	0.4		7.6	7.2	6.8	7.7	4.7
Stearidonic	18:4																					
Arachidic	20:0	0.3				0.4			1.2		0.1	0.3		8.3	0.5					0.3		0.4
Gondoic	20:1					0.2						0.2			0.3			0.3				0.4
Eicosadiensic	20:2											0.0										
Eicosatrienoic	20:3																					
Eicosatetraenoic	20:4																					
Eicosapentaenoic	20:5																					
Behenic	22:0					0.4	0.3				0.1				0.6			0.4				0.7
Erucic	22:1					0.0						0.0										0.2
Docosatetraenoic	22:4																					
Docosapentaenoic	22:5																					
Docosahexaenoic	22:6																					
Lignoceric	24:0					0.1						0.1										0.3
Nervonic	24:1					0.0						0.0										1.2
Other/Unknown							0.4	0.4			0.1					11.7	6.0					10.2
Total		99.1	100.0	100.0	100.0	99.2	100.0	99.6	100.0	100.0	96.6	99.7	100.0	99.9	99.4	88.1	94.0	99.8	100.0	98.8	100.0	89.8

[green] = not included in mean and S.D.   [blue] = 18:1 and 18:2 reversed from literature values

* Literature references identified in [square brackets].

9. Biodiesel from Soybean Oil (Page 2 of 2) *																			
[350]	[386]	[387]	[91]	[352]	[381]	[109]	[344]	[388]	[353]	[339]	[347]	[357]	[389]	[348]	[359]	[360]	[382]	Results	
																		mean	Dev
							0.0				0.0		0.1					0.0	0.0
							0.0				0.0							0.0	0.0
			0.1			0.0	0.0				0.0		0.4					0.1	0.2
		0.1		0.3		0.0	0.1	0.1			0.1		0.3			0.0	0.0	0.1	0.2
																		0.0	0.0
11.8	11.0	13.3	14.1	10.9	24.3	11.3	10.3	10.9	11.0	10.5	10.5	17.0	9.7	10.3	13.9	12.0	11.8	11.6	2.0
	0.1	0.7	0.3			0.1		0.1		0.2	0.1				0.3			0.2	0.3
																		0.1	0.1
3.2	3.3	4.8	5.2	3.2	20.3	3.6	4.7	4.2	2.0	4.1	4.3	3.0	4.4	3.8	2.1	3.0	3.2	3.9	0.8
23.3	25.4	24.5	25.3	24.0	37.4	24.9	22.5	25.0	20.0	24.1	24.2	26.0	23.1	22.7	23.2	23.0	23.3	23.7	2.4
55.5	53.6	55.4	48.7	54.5	2.5	53.0	54.1	52.7	64.0	53.6	51.4	54.0	53.9	55.1	56.2	55.0	55.5	53.8	3.5
6.3	5.3	0.1	6.1	6.8	0.7	6.1	8.3	6.2		7.7	7.5	3.0	8.3	7.5	4.3	6.0	6.3	5.9	2.6
	0.4	0.4		0.1		0.3		0.3			0.4			0.4		0.0	0.0	0.3	0.3
	0.3					0.3					0.3			0.2				0.3	0.1
																		0.0	
	0.4	0.5		0.1		0.0		0.1			0.4					0.0	0.0	0.3	0.2
						0.3	0.0				0.1					0.0		0.1	0.1
	0.1					0.1					0.1					0.0	0.0	0.1	0.1
						0.0												0.3	0.6
		0.7								3.0								4.1	4.7
100.0	99.8	99.3	100.0	100.3	85.2	100.0	100.0	99.6	97.0	100.2	99.3	103.0	100.0	100.0	100.0	99.0	100.0	100.8	

* Literature references identified in [square brackets].

Fatty Acid		[390]	[335]	[215]	[102]	[112]	[391]	[350]	[392]	[366]	[381]	[109]	[344]	[345]	[353]	[357]	[359]	[360]	[382]	Results	
Common Name	Abbrev.																			mean	Dev
Capriotic	6:0																				
Caprylic	8:0												0.0							0.0	
Capric	10:0												0.0							0.0	
Lauric	12:0	0.0										0.0	0.0	0.5						0.1	0.3
Tridecylic	13:0																				
Myristic	14:0	0.1									2.4	0.0	0.1	0.2				0.0	0.0	0.1	0.1
Myristoleic	14:1																				
Pentadanoic	15:0																				
Pentadecenoic	15:1																				
Palmitic	16:0	7.5	4.2	4.9	5.8	4.5	6.3	6.0	7.0	12.2	8.6	6.2	6.0	6.8	6.4	23.0	6.4	6.0	6.1	6.4	1.8
Palmitoleic	16:1	0.3								0.1		0.1		0.1	0.1		0.1			0.1	0.1
Hexadecadienoic	16:2																				
Hexadecatrienoic	16:3																				
Heptadecanoic	17:0	0.1																		0.1	
Heptadecenoic	17:1	0.1																		0.1	
Stearic	18:0	4.1	3.3	1.4	5.7	4.0	3.3	3.0	3.5	4.4	1.9	3.7	5.9	4.7	2.9	3.0	2.9	3.0	3.3	3.6	1.1
Oleic	18:1	30.4	27.6	18.9	20.4	82.0	20.6	17.0	33.3	25.3	11.6	25.2	16.0	18.6	17.7	24.0	17.7	17.0	16.9	21.7	5.3
Linoleic	18:2	54.4	63.6	66.0	66.0	8.0	68.3	74.0	55.2	51.4	77.9	63.1	71.4	68.2	72.8	49.0	72.9	74.0	73.7	66.3	7.6
Linolenic	18:3	1.7	0.2			0.2	0.1			6.3	8.2	0.2	0.6	0.5		1.0	0.0	0.0	0.0	1.5	2.6
Stearidonic	18:4																				
Arachidic	20:0	0.4			0.6	0.3	0.2					0.3		0.4			0.0	0.0		0.3	0.2
Gondoic	20:1	0.4					0.1					0.2					0.0			0.2	0.2
Eicosadiensic	20:2																				
Eicosatrienoic	20:3																				
Eicosatetraenoic	20:4																				
Eicosapentaenoic	20:5																				
Behenic	22:0	0.7	0.7	0.5	1.0	1.0	0.6					0.7					0.0	0.0		0.6	0.4
Erucic	22:1											0.1	0.0							0.1	0.1
Docosatetraenoic	22:4																				
Docosapentaenoic	22:5																				
Docosahexaenoic	22:6																				
Lignoceric	24:0		0.4				0.2					0.2					0.0	0.0		0.2	0.2
Nervonic	24:1											0.0								0.0	
Other/Unknown																0.1				0.1	
Total		100.0	100.0	91.7	99.5	100.0	99.6	100.0	99.0	99.7	110.6	100.0	100.0	100.0	99.9	100.0	100.0	100.0		101.2	

10. Biodiesel from Sunflower *

  = not included in mean and S.D.

* Literature references identified in [square brackets].

Fatty Acid		[158]	[335]	[93]	[391]	[393]	[381]	[69]	[164]	[344]	[345]	[394]	[353]	[389]	[348]	[359]	[395]	Results	
Common Name	Abbrev.																	mean	Dev
Capriotic	6:0							0.1										0.1	
Caprylic	8:0							0.0	0.0					0.1				0.0	0.0
Capric	10:0			0.1					0.1	0.1				0.1				0.1	0.0
Lauric	12:0	0.2	0.2	0.1					0.1	0.1				0.3				0.2	0.1
Tridecylic	13:0																		
Myristic	14:0	1.2	2.9	2.1	2.3	2.7		3.1	2.5	3.3	3.3	3.1		1.4	3.2		2.7	2.6	0.7
Myristoleic	14:1			0.3	0.2											0.5		0.3	0.2
Pentadanoic	15:0		0.6			0.9									0.3			0.6	0.3
Pentadecenoic	15:1														0.1			0.1	
Palmitic	16:0	18.9	24.3	23.8	19.1	25.3	23.2	27.6	28.4	25.2	25.5	25.2	29.0	23.8	23.7	23.3	23.0	24.3	2.8
Palmitoleic	16:1	2.1	2.1	3.3	2.5	2.0		2.5			3.4	3.7		2.6	3.8	0.1	2.9	2.6	1.0
Hexadecadienoic	16:2																		
Hexadecatrienoic	16:3																		
Heptadecanoic	17:0		1.2			1.7	1.3								1.5			1.4	0.2
Heptadecenoic	17:1		0.4												0.8			0.6	0.3
Stearic	18:0	8.9	22.8	14.8	13.3	34.7	13.0	25.0	15.7	19.2	21.6	18.5	24.5	13.8	18.4	19.3	19.4	18.2	4.5
Oleic	18:1	44.4	40.2	40.2	40.5	31.7	44.4	38.6	42.2	48.9	38.7	44.5	44.5	48.2	44.1	42.4	41.6	42.2	4.1
Linoleic	18:2	15.7	3.3	7.9	4.1	0.8	7.0	2.1	9.4	2.7	2.2	3.0		9.9	2.9	2.9	3.9	4.4	2.9
Linolenic	18:3	2.8	0.7	0.7	1.7				0.6	0.5	0.6	0.7			0.4	0.9	0.5	0.9	0.7
Stearidonic	18:4																0.4	0.4	
Arachidic	20:0	0.3	0.2	0.3	0.2	0.3			0.2		0.1				0.2		0.1	0.2	0.1
Gondoic	20:1	0.8	0.6						0.9						0.5		0.3	0.6	0.2
Eicosadiensic	20:2																		
Eicosatrienoic	20:3																		
Eicosatetraenoic	20:4																		
Eicosapentaenoic	20:5																		
Behenic	22:0	0.1		0.0					0.1									0.1	0.1
Erucic	22:1	0.0							0.1	0.0								0.0	0.1
Docosatetraenoic	22:4																		
Docosapentaenoic	22:5																		
Docosahexaenoic	22:6																		
Lignoceric	24:0	0.0																0.0	
Nervonic	24:1	0.0																0.0	
Other/unknown		1.8	0.5	3.4										1.3		2.9		2.0	1.2
Total		95.4	99.5	93.6	83.9	100.0	87.5	100.0	100.2	100.0	95.6	98.7	98.0	100.0	99.9	88.9	95.4	100.0	

11. Biodiesel from Tallow *

= not included in mean and S.D.

* Literature references identified in [square brackets].

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12. Biodiesel from Yellow Grease *																						
Fatty Acid		[111]	[390]	[396]	[163]	[335]	[222]	[211]	[189]	[215]	[380]	[342]	[187]	[89]	[397]	[386]	[163]	[69]	[347]	[395]	Results	
Common Name	Abbrev.																				mean	Dev
Capriotic	6:0																					
Caprylic	8:0																		0.0		0.0	
Capric	10:0																		0.0		0.0	
Lauric	12:0		0.1		0.0	0.1			0.0	1.6	0.1						0.0		0.0		0.2	0.6
Tridecylic	13:0																					
Myristic	14:0	0.2	0.5		0.2	0.5	0.1	1.7	0.9	1.5	1.9	0.9		0.1	0.8		0.3	0.7	1.7	0.7	0.8	0.6
Myristoleic	14:1																		0.0		0.0	
Pentadanoic	15:0															0.1					0.1	
Pentadecenoic	15:1																					
Palmitic	16:0	11.5	13.6	12.5	10.9	14.3	10.5	19.5	23.3	27.3	24.5	20.4	13.6	16.1	25.8	8.4	12.3	14.4	19.5	14.3	16.5	5.6
Palmitoleic	16:1	0.2	0.8		0.7	1.1	0.6	0.0	1.3			4.6		0.0	0.8	0.2	0.8	1.1	0.0	1.4	0.9	1.1
Hexadecadienoic	16:2																					
Hexadecatrienoic	16:3																					
Heptadecanoic	17:0		0.1		0.1	0.3	0.0								0.2		0.1				0.1	0.1
Heptadecenoic	17:1		0.1		0.1	0.2	0.1								0.1		0.1				0.1	0.0
Stearic	18:0	3.0	5.7		4.5	8.0	4.0	14.4	9.7	4.9	14.4	4.8	5.7	4.0	4.4	3.7	5.1	9.2	14.4	8.2	7.1	3.9
Oleic	18:1	27.9	43.4	49.6	60.4	35.6	54.7	54.7	49.7	36.1	38.3	52.9	43.4	31.4	37.1	34.6	51.9	48.6	54.7	43.3	44.6	9.3
Linoleic	18:2	34.8	33.6	29.7	21.5	35.0	28.0	8.0	15.1	25.7	13.4	13.5	33.6	46.1	28.2	50.5	27.6	23.7	8.0	26.3	25.1	10.3
Linolenic	18:3		0.6		0.4	4.0	0.3	0.7	0.0	1.9	0.3	0.8	0.4	2.3	0.4	0.6	0.5	2.3	0.7	2.5	1.1	1.1
Stearidonic	18:4																				0.5	0.5
Arachidic	20:0	0.3	0.3		0.4	0.3	0.4	0.3				0.1			0.6	0.4	0.4		0.3	0.3	0.3	0.1
Gondoic	20:1		0.6		0.4		0.4	0.5				0.8			0.5	0.4	0.5		0.5	0.5	0.5	0.1
Eicosadiensic	20:2																					
Eicosatrienoic	20:3																					
Eicosatetraenoic	20:4																					
Eicosapentaenoic	20:5																					
Behenic	22:0	0.3	0.5		0.4	0.3	0.7	0.2				0.0			0.7	0.8	0.5		0.2		0.4	0.2
Erucic	22:1					0.2						0.1							0.0		0.1	0.1
Docosatetraenoic	22:4								0.0												0.0	
Docosapentaenoic	22:5																					
Docosahexaenoic	22:6																					
Lignoceric	24:0											0.0			0.4	0.3			0.0		0.2	0.2
Nervonic	24:1										4.4										4.4	
Other/Unknown																						
Total		78.2	100.0	91.8	100.0	99.9	100.0	99.9	100.0	99.0	97.3	99.0	96.7	100.0	100.0	99.9	100.0	100.0	99.9	98.0	103.1	

= not included in mean and S.D.

* Literature references identified in [square brackets].

Appendix V. Fatty Acid Compositional Profiles from Microalgae

1. Bacillariophyta

2. Chlorophyta

3. Cryptophyta, Eustigmatophyta, Haptophyta

Appendix V. Fatty Acid Compositional Profiles from Microalgae

Common Name	Abbrev.	Chaetoceros calcitrans			Skeletonema costatum				Phaeodactylum tricornutum						
		[398]	mean	dev	[399]	[400]	mean	dev	[401]	[402]	[398]	[54]	[400]	mean	dev
Capriotic	6:0														
Caprylic	8:0														
Capric	10:0												24.6		24.6	
Lauric	12:0															
Tridecylic	13:0															
Myristic	14:0	18.6	18.6		16.4	12.7	14.6	2.6	5.5	4.3	12.7		7.4	7.5	3.7
Myristoleic	14:1				0.4	0.4	0.4	0.0				51.0	0.1	25.5	36.0
Pentadanoic	15:0					2.7	2.7					14.9	1.0	8.0	9.8
Pentadecenoic	15:1														
Palmitic	16:0	26.3	26.3		15.3	9.4	12.4	4.2	16.6	13.3	20.4		11.3	15.4	4.0
Palmitoleic	16:1	27.5	27.5		26.0	19.6	22.8	4.5	25.9	17.4	24.7		22.4	22.6	3.8
Hexadecadienoic	16:2				2.6	5.6	4.1	2.1	3.1	4.8			5.4	4.4	1.2
Hexadecatrienoic	16:3				10.0	10.3	10.2	0.2	10.4	2.1			12.3	8.3	5.4
Heptadecanoic	17:0					0.3	0.3						0.1	0.1	
Heptadecenoic	17:1														
Stearic	18:0	2.6	2.6		1.3	2.2	1.8	0.6		2.5	2.6		0.4	1.8	1.2
Oleic	18:1	4.5	4.5		3.1	2.6	2.9	0.4	2.4	1.5	15.1		2.8	5.5	6.5
Linoleic	18:2	0.8	0.8		1.2	1.6	1.4	0.3	2.0	1.0	2.7	0.6	1.5	1.6	0.8
Linolenic	18:3				1.5	0.2	0.9	0.9			0.3		1.4	0.9	0.7
Stearidonic	18:4				1.8	2.9	2.4	0.8					0.5	0.5	
Arachidic	20:0											1.3		1.3	
Gondoic	20:1										0.5	0.6		0.5	0.1
Eicosadiensic	20:2					0.2	0.2				0.9		0.2	0.5	0.5
Eicosatrienoic	20:3												0.1	0.1	
Eicosatetraenoic	20:4				1.4		1.4			3.7			0.6	2.2	2.2
Eicosapentaenoic	20:5	6.7	6.7		13.0	15.4	14.2	1.7	30.2	35.5	10.1		28.4	26.1	11.0
Behenic	22:0														
Erucic	22:1														
Docosatetraenoic	22:4														
Docosapentaenoic	22:5														
Docosahexaenoic	22:6	0.6	0.6		1.8	2.3	2.1	0.4		1.2	0.7		0.7	0.9	0.3
Lignoceric	24:0														
Nervonic	24:1														
Total		87.6	87.6		95.8	88.4	94.4		96.1	87.3	90.7	93.0	96.6	158.1	

16:4 = 7.5   11:0 = 7.01

* Literature references identified in [square brackets].

Appendix V Compositional Profiles (cont.)

Common Name	Abbrev.	Chlamydomonas reinhardtii			Chorella vulgaris						Dunaliella salina				Dunaliella teriolecta					
		[403]	mean	dev	[36]	[404]	[54]	[403]	mean	dev	[405]	[400]	mean	Dev	[36]	[54]	[403]	[400]	mean	dev
Capriotic	6:0						0.2		0.2										0.1	
Caprylic	8:0						0.6		0.6											
Capric	10:0						0.5		0.5								0.4			0.4	
Lauric	12:0						2.7		2.7		1.5		1.5		0.5	3.4			1.9	2.0
Tridecylic	13:0						0.7		0.7							1.8			1.8	
Myristic	14:0	2.3	2.3		3.1		1.2	3.1	2.5	1.1	0.6	0.5	0.6	0.1	1.5	1.1	0.3		1.0	0.6
Myristoleic	14:1						0.9		0.9		0.6	0.1	0.4	0.4	1.2		0.1		0.7	0.8
Pentadanoic	15:0						31.8		31.8			1.9	1.9		17.8		1.0		9.4	11.9
Pentadecenoic	15:1						2.4		2.4						2.4				2.4	
Palmitic	16:0	32.4	32.4		25.1	18.0	2.2	24.2	17.4	10.6	21.0	17.8	19.4	2.3	17.7	1.2	23.6	10.3	13.2	9.7
Palmitoleic	16:1	1.7	1.7		5.3	5.0	1.4	0.8	3.1	2.3	0.9	2.5	1.7	1.1	0.9	11.7	4.3	5.2	5.5	4.5
Hexadecadienoic	16:2	1.6	1.6			12.0		4.1	8.1	5.6		1.5	1.5		3.0		3.0	2.0	2.7	0.6
Hexadecatrienoic	16:3	2.1	2.1		1.3	2.1		4.4	2.6	1.6	10.3	4.1	7.2	4.4	1.2		2.6	4.7	2.8	1.7
Heptadecanoic	17:0						3.9		3.9							1.4			1.4	
Heptadecenoic	17:1						31.6		31.6							4.1			4.1	
Stearic	18:0				0.6		1.1	1.4	1.0	0.4		1.5	1.5			4.9		0.3	2.6	3.3
Oleic	18:1	17.7	17.7		12.6	9.2	12.0	3.1	9.2	4.4	7.1	3.4	5.3	2.6	4.9	12.0	3.9	2.2	5.7	4.3
Linoleic	18:2	10.8	10.8		7.2	43.0	1.4	31.0	20.7	19.6	6.2	6.1	6.2	0.1	12.4	27.8	11.6	5.2	14.2	9.6
Linolenic	18:3	21.6	21.6		19.1	10.0	0.0	28.0	14.3	12.0	38.0	39.4	38.7	1.0	30.2		33.1	41.9	35.0	6.1
Stearidonic	18:4											0.7	0.7						1.3	1.3
Arachidic	20:0				0.1		2.9		1.5	2.0										
Gondoic	20:1				0.9				0.9											
Eicosadiensic	20:2										0.1		0.1							
Eicosatrienoic	20:3				0.8				0.8											
Eicosatetraenoic	20:4				0.2		0.5		0.4	0.2						0.3		0.3	0.3	0.0
Eicosapentaenoic	20:5				0.5				0.5			0.1	0.1						0.4	0.4
Behenic	22:0																			
Erucic	22:1																			
Docosatetraenoic	22:4																			
Docosapentaenoic	22:5																			
Docosahexaenoic	22:6						0.5		0.5											
Lignoceric	24:0						0.5													
Nervonic	24:1						0.5													
Total		90.0	90.0		76.7	99.3	99.6	99.9	158.7		86.2	79.7	86.6		70.8	91.9	83.1	75.2	107.0	

16:4 = 9.9   16:4 = 4.06   16:4 = 18.2   16:4 = 10.56   16:4 = 16.7   16:4 = 23.9

* Literature references identified in [square brackets].

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Chlorophyta (Page 2 of 2) *

Common Name	Abbrev.	Scenedesmus obliquus				Neochloris oleabundans				
		[36]	[54]	mean	dev	[406]	[407]	[36]	mean	dev
Capriotic	6:0									
Caprylic	8:0									
Capric	10:0		1.0	1.0						
Lauric	12:0		0.5	0.5						
Tridecylic	13:0		0.2	0.2						
Myristic	14:0	1.5	0.3	0.9	0.9	3.8	1.6	0.4	1.9	1.7
Myristoleic	14:1		21.7	21.7			0.4		0.4	
Pentadanoic	15:0		2.3	2.3			1.4		1.4	
Pentadecenoic	15:1		6.2	6.2						
Palmitic	16:0	21.8	1.4	11.6	14.4	74.6	15.0	19.4	36.3	33.2
Palmitoleic	16:1	6.0	5.2	5.6	0.6	2.2	3.5	1.9	2.5	0.9
Hexadecadienoic	16:2	4.0	2.4	3.2	1.2		2.5	1.7	2.1	0.6
Hexadecatrienoic	16:3	0.7		0.7				1.0	1.0	
Heptadecanoic	17:0		20.4	20.4			11.7		11.7	
Heptadecenoic	17:1		1.2	1.2			1.0		1.0	
Stearic	18:0	0.4	19.5	10.0	13.5	3.1	11.0	1.0	5.0	5.3
Oleic	18:1	17.9	1.2	9.5	11.8	13.8	36.0	20.3	23.4	11.4
Linoleic	18:2	21.7	13.3	17.5	6.0		7.4	13.0	10.2	4.0
Linolenic	18:3	3.7	0.1	1.9	2.6	2.5		17.5	10.0	10.6
Stearidonic	18:4	0.2		0.2				2.1	2.1	
Arachidic	20:0		2.0	2.0			2.1		2.1	
Gondoic	20:1						2.5		2.5	
Eicosadiensic	20:2		0.4	0.4						
Eicosatrienoic	20:3									
Eicosatetraenoic	20:4									
Eicosapentaenoic	20:5									
Behenic	22:0									
Erucic	22:1									
Docosatetraenoic	22:4									
Docosapentaenoic	22:5									
Docosahexaenoic	22:6									
Lignoceric	24:0									
Nervonic	24:1									
Total		77.9	99.1	116.9		100.0	96.1	78.3	113.7	

16:4 = 7.2

* Literature references identified in [square brackets].

Common Name	Abbrev.	Cryptophyta * Chroomonas salina					Eustigmatophyta * Nannochloropsis oculata					Haptophyta * Isochrysis galbana				
		[408]	[409]	[400]	mean	dev	[410]	[406]	[400]	mean	Dev	[402]	[406]	[411]	mean	dev
Capriotic	6:0															
Caprylic	8:0															
Capric	10:0															
Lauric	12:0	6.4	0.8		3.6	3.9										
Tridecylic	13:0															
Myristic	14:0	34.5	21.6	5.0	20.4	14.8	3.5	3.8	3.9	3.7	0.2	4.8	15.1	11.8	10.6	5.3
Myristoleic	14:1			0.3	0.3				0.2	0.2					0.0	0.0
Pentadanoic	15:0	8.2	0.3	2.0	3.5	4.2			1.8	1.8						
Pentadecenoic	15:1															
Palmitic	16:0	18.1	18.5	13.5	16.7	2.8	17.9	36.4	20.5	24.9	10.0	12.3	12.4	16.7	13.8	2.5
Palmitoleic	16:1	1.2	2.2	2.0	1.8	0.6	19.0	25.8	25.2	23.3	3.8	21.7	4.0	3.8	9.8	10.3
Hexadecadienoic	16:2		0.7		0.7				0.8	0.8						
Hexadecatrienoic	16:3								0.6	0.6						
Heptadecanoic	17:0	0.9		1.4	1.1	0.4			1.1	1.1						
Heptadecenoic	17:1															
Stearic	18:0	2.4	1.2	3.0	2.2	0.9	0.7	3.7	1.8	2.1	1.5	1.2		1.1	1.2	0.1
Oleic	18:1	14.6	18.5	5.2	12.8	6.8	5.6	7.6	4.1	5.8	1.8	6.1	20.6	20.4	15.7	8.3
Linoleic	18:2	6.2	20.4	1.2	9.3	10.0	7.4	1.2	2.2	3.6	3.3	2.2	4.0	7.0	4.4	2.4
Linolenic	18:3	5.4	9.2	10.8	8.5	2.8	6.7		0.9	3.8	4.1	1.5		4.3	2.9	2.0
Stearidonic	18:4	0.9	2.9	30.3	11.4	16.4						7.2	20.8	13.4	13.8	6.8
Arachidic	20:0															
Gondoic	20:1	0.2	0.1		0.2	0.1										
Eicosadiensic	20:2								0.1	0.1						
Eicosatrienoic	20:3						0.4		0.3	0.4	0.1					
Eicosatetraenoic	20:4		0.8	2.8	1.8	1.4	3.7	4.6	5.3	4.5	0.8			0.5	0.5	
Eicosapentaenoic	20:5	0.7	1.4	12.9	5.0	6.9	37.1	15.9	29.7	27.6	10.8	25.6		0.6	13.1	17.7
Behenic	22:0															
Erucic	22:1															
Docosatetraenoic	22:4															
Docosapentaenoic	22:5		0.1		0.1							1.2			1.2	
Docosahexaenoic	22:6	0.8	0.7	7.1	2.9	3.7						8.1	17.6	17.4	14.4	5.4
Lignoceric	24:0															
Nervonic	24:1															2.3
Total		100.2	99.4	97.5	102.0		102.0	99.0	98.5	104.3		91.9	94.5	96.7	101.2	

* Literature references identified in [square brackets].

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Appendix VI. Physical/Chemical Properties of Biodiesel (FAME) from Fats and Oils

1. Camelina

2. Canola

3. Coconut

4. Corn

5. Jatropha

6. Palm

7. Rapeseed

8. Safflower

9. Soy

10. Sunflower

11. Tallow

12. Yellow Grease

Appendix VI. Physical/Chemical Properties of Biodiesel (FAME) from Fats and Oils

1. Biodiesel from Camelina *									
Property	[336]	[335]	[336]	[412]	[413]	[338]	[339]	Results mean	Results dev
Sulfur Content, ppm		1					3	2	2
Viscosity @ 40 °C, mm²/s		4.37	6.54*	3.03	3.47	4.00	4.15	3.80	0.55
Cloud Point, °C	3	2					3	3	1
Pour Point, °C	-4			-10	-9	-9	-4	-7	3
CFPP, °C	-3	-1	-5				-3	-3	2
Flash Point, °C				136				136	
Cetane No.				50.2	49.3	49.4	52.8	50.4	1.6
Cetane Index									
Iodine No.			154.5				151.0	152.8	2.5
Specific Gravity		0.888	0.884	0.875	0.889	0.875		0.882	0.007
LHV, MJ/Kg									
HHV, MJ/Kg				45.6	45.1	45.0		45.2	0.3

        = LHV/HHV not specified
        = Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature
* Literature references identified in [square brackets].

Property	[253]	[414]	[335]	[45]	[415]	[341]	[92]	[129]	[187]	[416]	[417]	[344]	[339]	[346]	[418]	Results mean	Results dev
2. Biodiesel from Canola *																	
Sulfur Content, ppm	2		1				3						2			2	0
Viscosity @ 40 °C, mm^2/s	4.40	4.60	4.44		4.49	4.48	4.40	4.63	3.90	2.7*	4.61	3.70	4.42	4.51	4.34	4.38	0.27
Cloud Point, °C			-3	-3			-3	-3	-2		-3		0			-2	1
Pour Point, °C				-4				-4	-6	-3	-12		-9		-8	-6	3
CFPP, °C			-13		-8	-14		-4			-7		-7			-9	4
Flash Point, °C							163	163	146					184	107	153	29
Cetane No.	53.6						51.5	53.9	52.9	56.0				54.0		53.7	1.5
Cetane Index															61.5	61.5	
Iodine No.		107.5											110.0	109.0		108.8	1.3
Specific Gravity	0.884	0.880	0.882		0.883		0.883	0.881	0.882	0.890				0.884	0.884	0.883	0.003
LHV, MJ/Kg	37.8								40.0							38.9	1.6
HHV, MJ/Kg					39.0			40.1		44.8						41.3	3.1

= LHV/HHV not specified
= Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature
* Literature references identified in [square brackets].

Appendix VI Physical/Chemical Properties (cont.)

3. Biodiesel from Coconut *									
Property	[335]	[419]	[181]	[344]	[354]	[355]	[356]	Results mean	Results dev
Sulfur Content, ppm	3	3	2					3	1
Viscosity @ 40 °C, mm²/s	2.73	2.66	2.70	2.32	2.83	3.07	2.94	2.75	0.24
Cloud Point, °C	0	-5			-3			-3	3
Pour Point, °C			-5		-12			-9	5
CFPP, °C	-4				-5			-5	1
Flash Point, °C	115	107			110	120		113	6
Cetane No.		70.0	57.0		51.0			59	10
Cetane Index									
Iodine No.						7.0	30.0	19	16
Specific Gravity	0.807		0.874		0.873	0.872	0.875	0.874	0.001
LHV, MJ/Kg			35.2					35	
HHV, MJ/Kg							38.1	38	

= LHV/HHV not specified

= Data not included in mean and S.D.

* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

Appendix VI Physical/Chemical Properties (cont.)

4. Biodiesel from Corn *								
Property	[335]	[215]	[416]	[100]	[418]	[109]	Results	
							Mean	dev
Sulfur Content, ppm	5	3					4	1
Viscosity @ 40 °C, mm^2/s	4.38	4.36	2.55*	3.62	4.18	4.40	4.19	0.33
Cloud Point, °C	-3						-3	
Pour Point, °C			-4		-1		-2	2
CFPP, °C	-3					-12	-8	6
Flash Point, °C		167		154	192	170	171	16
Cetane No.		55.4	58.7			53.0	55.7	2.9
Cetane Index					60.9		60.9	
Iodine No.						101.0	101.0	
Specific Gravity	0.885	0.886	0.885	0.873	0.884		0.883	0.005
LHV, MJ/Kg		39.9					39.9	
HHV, MJ/Kg			45.0	41.1			43.1	2.7

    = LHV/HHV not specified

    = Data not included in mean and S.D.

   * = Viscosity measured at different / unspecified temperature

  * Literature references identified in [square brackets].

5. Biodiesel from Jatropha *

Property	[420]	[421]	[158]	[422]	[87]	[335]	[423]	[424]	[103]	[239]	[425]	[183]	[426]	[157]	[427]	[416]	[361]	[362]	[25]	[363]	[428]	[366]	[367]	mean	dev
Sulfur Content, ppm						1				1		0		1	10	15									5	6
Viscosity @ 40 °C, mm^2/s	7.20*	5.12	5.23	5.65	4.40	4.25	5.85	4.50	4.34	4.50	5.40	3.00*	4.34	4.34	4.13	2.41*	4.02	5.11		4.84	4.23	4.44	5.65	4.75	0.58
Cloud Point, °C	6				4	3												3			10			5	3
Pour Point, °C	4								3				3		-2	-5	-8				4			0	5
CFPP, °C						0																		0	
Flash Point, °C	248	168		170	163			130	135	130	162		135	130	164		117	161		191	148	163	170	152	20
Cetane No.	57.1		57.8		57.1			54.9	58.4	54.9		55.0	58.4	52.7	55.0	60.6				51.0		57.1	50.0	55.7	3.0
Cetane Index																									
Iodine No.																			109.5					109.5	
Specific Gravity	0.876	0.882	0.888	0.870		0.880		0.870	0.879	0.870	0.870	0.850	0.879	0.874	0.883	0.885	0.883				0.879	0.873	0.880	0.876	0.009
LHV, MJ/Kg			36.9																			38.5		37.7	
HHV, MJ/Kg	42.6	41.6	39.5	38.5				39.0		39.0	39.8	41.0			43.0	40.6	41.7	40.0			42.7			40.7	1.5

= LHV/HHV not specified
= Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

6. Biodiesel from Palm (Page 1 of 2) *																						
Property	[376]	[429]	[430]	[431]	[432]	[421]	[62]	[147]	[158]	[134]	[87]	[139]	[335]	[215]	[433]	[171]	[207]	[93]	[90]	[434]	[239]	[435]
Sulfur Content, ppm			6		1		2	3					1	5		1		1	2			
Viscosity @ 40 °C, mm^2/s	5.80*	3.72	4.46	5.70	7.11*	5.43	4.40	3.70		4.26	4.50	4.58	4.57	4.70		4.40		4.40	5.31*	5.70	4.50	4.39
Cloud Point, °C			15	13							16		13	15		14		12	12	13		
Pour Point, °C									18	14		12							13			
CFPP, °C		-5						0					12						13			9
Flash Point, °C			175	164		174		130		80	135	152		189		166			174	164	127	168
Cetane No.		55.0		62.0	64.0		65.0	58.0		61.6	54.6			62.0		64.0		60.0			54.6	63.7
Cetane Index												48.5				49.3			58.3			
Iodine No.			52.7					45.0	51.0										51.6	62.0		57.0
Specific Gravity	0.871	0.837	0.876	0.880	0.878	0.870	0.879	0.876	0.876	0.871			0.876	0.878		0.873	0.865	0.875	0.875	0.880	0.875	0.876
LHV, MJ/Kg	36.9		38.7	40.1	0.2	36.9	40.2	37.2							37.9		38.4			33.5		
HHV, MJ/Kg		45.1							39.8	40.3				39.9			41.0				41.3	

= LHV/HHV not specified
= Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

| 6. Biodiesel from Palm (Page 2 of 2) * | | | | | | | | | | | | | | | | | | | | | | Results | |
[436]	[437]	[181]	[438]	[89]	[110]	[439]	[209]	[378]	[440]	[248]	[441]	[366]	[100]	[85]	[109]	[442]	[344]	[443]	[339]	[75]	[444]	mean	dev
	0	2				2	2			2									2			2	2
5.51*	5.58	4.50	4.73	4.52		4.44	4.53	5.97*	5.70		4.71	4.51	3.94	4.01	4.50	4.39	3.87	7.11*	4.58	5.70	4.40	4.61	0.56
13	15		16	15		15					16				10				17	13		14	2
13	14	13	12	12		12									10	14			15			13	2
12			11	12	10	13					12				10				12			9	5
						173		182				163	161		176	105*				164		163	17
61.4	62.0	64.5	62.0			69.5	63.5		62.0	63.8		57.1			61.0	64.0		64.0		62.0	67.2	61.9	3.6
								47.6								48.8						50.5	4.4
						54.0		49.4						50.0	67.0				54.0			54.0	6.1
0.875	0.871	0.874	0.872			0.871	0.876	0.871	0.880	0.878	0.864		0.867	0.870		0.881		0.878		0.880	0.875	0.873	0.008
	37.1	36.9	37.1			36.8	37.1			40.1								40.0		33.5	32.4	37.3	2.3
						39.4	39.8	40.3			39.8		41.2			39.5						40.6	1.5

* Literature references identified in [square brackets].

Property	[376]	[429]	[111]	[225]	[445]	[432]	[62]	[234]	[147]	[158]	[446]	[215]	[90]	[447]	[186]	[448]	[449]	[380]	[450]	[239]	[436]	[236]
7. Biodiesel from Rapeseed (Page 1 of 2) *																						
Sulfur Content, ppm			4	5	6	6	2	2	3		0	1	2	2		1					7	
Viscosity @ 40 °C, mm^2/s	5.90*	3.73	4.14	4.48	4.64	6.38*	4.50	4.31	4.58	4.49	4.24	4.59	5.58*	4.45	5.65	4.48		4.55	4.80	4.50	5.19*	4.42
Cloud Point, °C								-5					-4		0	-4	-6	2	-3		-4	
Pour Point, °C								-10		-12			-10		-15		-12	-1			-3	
CFPP, °C		-9	-3		-22			-5	-14				-12	-18							-5	
Flash Point, °C					131			174	145			177	178	176	179		200		153	152		173
Cetane No.		55.0		54.7	56.1	53.0	59.0	52.8	52.5	52.2		54.5		51.0	61.8	48.0	58.7	53.9		51.6	54.0	53.1
Cetane Index								61.8					58.0						52.0			
Iodine No.			125.8						113.0	110.0	130.1		114.1									
Specific Gravity	0.879	0.835	0.884	0.884	0.883	0.873	0.884	0.884	0.881	0.883	0.886	0.885	0.884	0.883		0.885		0.880	0.893	0.882	0.883	0.884
LHV, MJ/Kg	37.1		39.0	37.0	39.8	37.0	37.0		37.4	37.0					37.8		37.8	39.8		37.7		36.8
HHV, MJ/Kg		45.0							38.0	40.0	39.7	39.9			40.5		40.4		40.0			

= LHV/HHV not specified

= Data not included in mean and S.D.

* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

																	Results	
[40]	[110]	[439]	[451]	[226]	[452]	[453]	[100]	[454]	[85]	[231]	[109]	[241]	[455]	[443]	[456]	[444]	mean	dev
		2	8	2				10				3			5		4	3
4.50		4.48	4.50	4.56	4.15	4.57	4.60	4.50	4.11	5.51	4.40	4.40	6.70*	6.38*	4.48	4.20	4.50	0.35
-5		-5			-3	-2			-5				-2				-3	2
		-12			-9	-7			-13				-9				-10	3
	-20	-12	-14	-20	-9							-10					-12	6
		172		182	165	162	180					170	93*	84*			169	16
51.0		56.6	51.0	51.0				51.7				55.0	54.4	53.0	54.7	55.0	53.7	2.9
						49.6						52.0					54.7	5.0
		113.0						115.0	114.0	117.0	109.0						116.1	6.7
0.885		0.880		0.883	0.869	0.872	0.857		0.880			0.881		0.873	0.884	0.882	0.879	0.010
37.5		37.2		40.0						38.2		37.9		39.8	36.1	32.8	37.6	1.6
		39.7			44.9	44.9	41.6							40.4			41.1	2.3

* Literature references identified in [square brackets].

8. Biodiesel from Safflower *						
Property	[452]	[100]	[85]	[457]	Results	
					Mean	dev
Sulfur Content, ppm						
Viscosity @ 40 °C, mm^2/s	4.29	4.03	4.11		4.14	0.13
Cloud Point, °C	-2		-5		-4	2
Pour Point, °C	-8		-8	-6	-7	1
CFPP, °C	-6				-6	
Flash Point, °C	176	167		180	174	7
Cetane No.	52.3			49.8	51.1	1.8
Cetane Index						
Iodine No.			141.0		141.0	
Specific Gravity	0.880	0.866	0.890		0.879	0.012
LHV, MJ/Kg						
HHV, MJ/Kg	45.2	41.3		40.1	42.2	2.7

= LHV/HHV not specified

= Data not included in mean and S.D.

* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

9. Biodiesel from Soybean Oil (Page 1 of 3) *																						
Property	[244]	[376]	[240]	[191]	[431]	[233]	[432]	[253]	[190]	[148]	[159]	[87]	[65]	[149]	[414]	[335]	[45]	[93]	[189]	[178]	[433]	[215]
Sulfur Content, ppm			1				1	6	4	5	4					1		0	0			3
Viscosity @ 40 °C, mm²/s	3.93	5.40*	4.12		4.50	4.97	6.62*	4.10	4.32	4.40	4.10	4.00	4.15	4.40	4.10	4.04	4.10		4.07			3.28
Cloud Point, °C			-2		1							4				1	0	0	-1			
Pour Point, °C					-7												-4		-3			
CFPP, °C										-5				-7		-4						
Flash Point, °C			161		178	144			157			160						140	142			173
Cetane No.	48.0		53.0		45.0	52.9	51.0	50.6	47.5	51.5		58.1		52.0				49.0	47.4			51.3
Cetane Index																						
Iodine No.										118.0	132.5			122.0	124.6				127.4			
Specific Gravity		0.881	0.882		0.885	0.896	0.873	0.883		0.882	0.880			0.882	0.881	0.884			0.885			0.885
LHV, MJ/Kg	37.5	36.7		36.6	37.9	38.3	40.0	37.6			37.3										38.1	
HHV, MJ/Kg										38.6	39.8			38.6						38.1		39.7

= LHV/HHV not specified

= Data not included in mean and S.D.

* = Viscosity measured at different / unspecified temperature

* Literature references identified in [square brackets].

9. Biodiesel from Soybean Oil (Page 2 of 3) *																				
[90]	[129]	[458]	[459]	[460]	[461]	[385]	[380]	[434]	[450]	[239]	[436]	[64]	[89]	[110]	[439]	[462]	[185]	[387]	[440]	[172]
0	0														3	2		0		4
5.10*	4.55	4.11	4.06	4.70	4.33	3.90	4.63	4.50	4.08	4.10	5.05	4.13	4.06		4.24		5.20	5.75	4.10	4.40
-1	3		-1	3		0	-3	1	2		-2	-2	2		-1					
0	-4		-7	-7	0		-4	-7			0		-3		-6					
-3	-2		-4								-4		-3	-3	-3			-5		-7
168	167			341				178	141	120					180		166	168		187
	59.0	43.3	45.8	51.6	45.7	54.7	59.0	45.0		59.0	49.6	57.6			50.6	52.1			46.0	52.0
									47.0								47.0	56.0		
127.7															127.0					122.0
0.885	0.888	0.887		0.887				0.885	0.884	0.889	0.885	0.879			0.883	0.886	0.870	0.883	0.884	0.882
		37.3				37.1	39.6	33.6				37.4			36.9	37.5	38.8			
	39.9	39.8	39.5	39.7	39.8				39.8	39.7					39.4	40.1				38.6

* Literature references identified in [square brackets].

9. Biodiesel from Soybean Oil (Page 3 of 3) *																Results	
[153]	[210]	[91]	[463]	[100]	[464]	[418]	[109]	[465]	[344]	[339]	[466]	[389]	[467]	[444]	[468]	mean	Dev
5	2							6		1						2	2
4.38	4.02	4.34	4.41	4.08	4.13	3.97	4.20	4.20	3.67	4.12	4.59	4.06	4.50	4.00	4.09	4.26	0.39
	-1	3			1					0		3	1		-2	0	2
	-2	-3	14*			0				-3		-7	-7			-4	3
-9		-3					-5			-4						-4	2
			168	168	145	139	171	164				127	178		141	159	18
52.0	57.5		61.3		51.7		49.0	67*			50.4		45.0	50.9		51.3	4.6
						60.1						51.6				52.3	5.7
117.0							128.0			134.0						125.5	5.4
0.883	0.884		0.863	0.865	0.915*	0.885		0.887			0.880	0.887	0.885	0.855	0.883	0.882	0.007
	37.5				33.6						37.4		33.5	32.7	38.4	37.0	1.9
40.7			41.1	41.3								40.1				39.7	0.8

* Literature references identified in [square brackets].

Property	[431]	[421]	[216]	[87]	[390]	[335]	[182]	[215]	[434]	[450]	[440]	[392]	[366]	[100]	[418]	[109]	[469]	[470]	[471]	[472]	Results mean	Results Dev
10. Biodiesel from Sunflower *																						
Sulfur Content, ppm						0		4													2	3
Viscosity @ 40 °C, mm^2/s	4.60	6.74*	4.40	4.10	4.40	4.44	4.50	4.38	4.60	4.20	4.60	4.85	4.10	4.16	4.03	4.20	4.90	4.22	4.79	4.60	4.42	0.26
Cloud Point, °C	1			4		3			1			1					1	0	3	1	2	1
Pour Point, °C												-3			-1		-4	-4	0		-2	2
CFPP, °C						-3						-1				-3	-1		-3		-2	1
Flash Point, °C	183	178		180			185	183	183	164		168	73	166	157	177	170		85	183	175	9
Cetane No.	49.0		51.3	55.6				54.5	49.0		49.0	55.0	55.6			50.0		46.6	49.0	49.0	51.1	3.2
Cetane index										49.0					60.9						55.0	8.4
Iodine No.			125.4													132.0					128.7	4.6
Specific Gravity	0.860	0.882	0.886		0.886	0.880	0.890	0.886	0.860	0.880	0.880	0.884		0.863	0.884		0.880		0.887	0.860	0.878	0.011
LHV, MJ/Kg			37.1		37.1				33.5											33.5	35.3	2.1
HHV, MJ/Kg	39.0	39.7			39.7		39.3	40.0	39.6	40.1		45.5		41.3			45.3	39.8	38.1		40.6	2.4

= LHV/HHV not specified
= Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature
* Literature references identified in [square brackets].

11. Biodiesel from Tallow *													Results	
Property	[431]	[253]	[158]	[335]	[93]	[129]	[434]	[440]	[164]	[389]	[473]	[393]	mean	Dev
Sulfur Content, ppm		18		7	3	0			48				7	8
Viscosity @ 40 °C, mm²/s		4.80	4.42	4.82	4.53	4.92		4.10	5.23	4.11		5.30	4.69	0.44
Cloud Point, °C	12			16	12	18	12			12	12		13	2
Pour Point, °C	9		9			15	9			9	9		10	3
CFPP, °C				14		12			10			14	13	2
Flash Point, °C	96				170	154	96			96	96	157	124	35
Cetane No.		57.5	57.2		62.4	59.6		58.0					58.9	2.1
Cetane Index										57.8		60.4	59.1	
Iodine No.			77.0						54.9				65.9	15.6
Specific Gravity		0.875	0.878	0.874	0.876	0.874		0.887	0.887	0.877		0.872	0.878	0.006
LHV, MJ/Kg		37.1	37.4						37.2				37.2	0.2
HHV, MJ/Kg			39.5			39.8				39.9			39.7	0.2

= LHV/HHV not specified
= Data not included in mean and S.D.
* = Viscosity measured at different / unspecified temperature
* Literature references identified in [square brackets].

12. Biodiesel from Yellow Grease (Page 1 of 2) *																				
Property	[111]	[474]	[233]	[432]	[421]	[475]	[476]	[253]	[216]	[251]	[165]	[390]	[396]	[163]	[335]	[45]	[415]	[222]	[211]	[129]	[189]
Sulfur Content, ppm	3	2		7				15		2		0			6			0		0	15
Viscosity @ 40 °C, mm²/s	4.50	4.70	4.39	6.89*	4.73	4.31	4.49	4.80	5.14	4.30	4.42	4.92	5.43	5.92	4.55		4.40	5.16	5.92	5.14	4.74
Cloud Point, °C		13													6	8				16	7
Pour Point, °C											6					8				8	
CFPP, °C	-4		3												2		10	-6		6	3
Flash Point, °C	179				200		122													154	140
Cetane No.			57.8	56.0				61.2	65.2	52.9							60.4		62.6	52.7	55.6
Cetane Index						44.3	44.3														
Iodine No.	116.0								101.6												78.8
Specific Gravity	0.884	0.885	0.877	0.870	0.885	0.887	0.860	0.876	0.883	0.883	0.879	0.884	0.884	0.885	0.883		0.875		0.872	0.878	
LHV, MJ/Kg		38.1	38.4	40.1	38.7			37.3	36.9	36.8	36.9	36.9		36.9				36.6	37.7		
HHV, MJ/Kg						41.4	41.2					39.5	36.8	39.6			38.7	39.3	40.1	40.0	

　　= LHV/HHV not specified
　　= Data not included in mean and S.D.
*　　= Viscosity measured at different / unspecified temperature
* Literature references identified in [square brackets].

	[215]	[380]	[187]	[437]	[477]	[89]	[397]	[478]	[248]	[479]	[163]	[480]	[136]	[481]	[482]	[468]	Results mean	Results dev
12. Biodiesel from Yellow Grease (Page 2 of 2) *																		
	3			1				7	7		0			6			5	5
	4.87	5.85	4.92	5.10	4.60	4.55	4.35	4.23		4.60	5.42	4.40	4.60	4.98	4.60	4.14	4.80	0.48
		11	3		-7	5				2						4	8	5
		14	-3		-4	-3				-3							3	7
					-5	-3		1		-4		10		0			1	5
	167		156		75			171		158		71					161	22
	55.0	63.2	52.0	55.5				54.5	55.6			60.4			51.0	53.4	56.9	4.2
							54.0			51.4							48.5	
					83.0		83.0				94.9	62.0		92.0			88.9	16.2
	0.884		0.888	0.883	0.842		0.886	0.890	0.870	0.887	0.884	0.875	0.871	0.880	0.871	0.881	0.879	0.010
		39.7	39.6	37.0				32.9	40.1		36.9		37.5		37.5	37.5	37.6	1.6
	39.7									38.4	39.6	38.7		39.4			39.4	1.1

* Literature references identified in [square brackets].

Appendix VIIa. Literature Sources used to Assess Biodiesel Emissions Impacts: HD/MD Engine Dynamometer Tests

Ref. No.*	Engine			Test Cycle	Base Fuel	Biodiesel Fuel	
	Year	Make	Model			Source	Blend Level
[483]	1987	DDC	6V92TA-83	FTP Hot	No.2DF	Soy, Rapeseed	6,10,20,30,40
[484]	2000	Cummins	B5.9	AVL 8	ULSD, No.2DF	Soy	20
[485]	1990	John Deere	CD6068TL052	ISO-8178_C1	No.2DF	Rapeseed	100
			6081T				
[458]	1988	DDC	6V92TA	FTP,Custom	No.2DF	Soy	10,20,30,50,100
	1991	DDC	Series 60	FTP Hot			10,20
[486]	1994	NAVISTAR	T444E	FTP Hot	No.2DF	Soy	20,50,100
[487]	1991	DDC	Series 60	FTP	No.2DF	Soy	20,35,65,100
[488]	1998	Caterpillar	3126E	FTP Hot	ULSD	Canola	20
[489]	1977	DDC	6V-71N	FTP	No.2DF	Soy	20
				UDDS			
[490]	1977	DDC	6V-71N-77	FTP	No.2DF	Soy	20
[491]	1989	DDC	6V92TA	FTP	No.2DF	Soy	20,30
[491]	1988	DDC	6V92TA	ORTECH EPA	No.2DF	Soy	20,30
[492]	2001	International	DT466E	FTP Cold, FTP Hot	ULSD	Soy	20
[493]	1991	DDC	6V92TA	FTP, FTP Hot	No.2DF	Soy, Tallow	20
[129]	1991	DDC	Series 60	FTP Hot	No.2DF	Soy	100
[255]	1991	DDC	Series 60	FTP	No.2DF	Soy	20,35,65,100
{Graboski, 2003 GRABOSKI2000 /id}	1991	DDC	Series 60	FTP Cold, FTP Hot	No.2DF	Tallow, Yellow Grease, Soy, Canola, Lard	20,100
[495]	1994	VOLVO	THD103KF	Steady state/ECE R49	No.2DF	Rapeseed	100
{Knothe, 2005 KNOTHE2006 /id}	2003	DDC	S60	FTP Hot	No.2DF	Soy	100
[447]	2007	MAN	D08 36 LFL51	ESC	ULSD	Rapeseed	20,100
	2000	Mercedes-Benz	OM 906 LA	ETC			5,10,20,30,40,100
[341]	2000	Mercedes-Benz	OM 906 LA	ESC	ULSD	Rapeseed	100
[134]		Mitsubishi	6D14	ASTM	ULSD	Palm	20,100
[497]	1991	DDC	Series 60	FTP Hot	No.2DF	Soy	5
[498]	1991	DDC	6V92TA	FTP	No.2DF	Soy	10,20,30,40
[465]	1992	Cummins	L10E	FTP	No.2DF	Soy	20,30
[499]	1991	Cummins	L10	Custom	No.2DF	Yellow Grease, Tallow	20,30,100
[500]	2002	Cummins	B5.9	FTP Hot	ULSD	Beef Tallow, Canola, Soy, Yellow Grease	10,20,50,100
	2003	DDC	Series 60			Beef Tallow, Soy + Beef Tallow, Soy	20
[202]	1989	DDC	6V92TA	FTP Hot	No.2DF	Soy	8.9
			Series 60				17.7
[189]	1991	DDC	Series 60	FTP,FTP Hot	No.2DF	Soy, Yellow Grease	20,50,100

Appendix VIIa. Literature Sources used to Assess Biodiesel Emissions Impacts: HD/MD Engine Dynamometer Tests (cont.)

Ref. No.*	Engine			Test Cycle	Base Fuel	Biodiesel Fuel	
	Year	Make	Model			Source	Blend Level
[256]	1991	DDC	Series 60	FTP	No.2DF	Soy, Yellow Grease	20,100
[385]	1983	Caterpillar	3304PCNA	ISO-8178_C1	No.2DF	Soy	30,100
[501]		International	7.31	AVL 8	No.2DF	Rapeseed	100
[178]	2002	Cummins	ISB	Custom	ULSD	Soy	20
[260]	1999	Cummins	ISM 370	FTP	No.2DF	Soy, Tallow	20
	2004	Cummins	ISM 370				
[502]	1987	Cummins	N-14-87	FTP	No.2DF	Soy	10,20
[448]	1990	Scania	DS9 52	R49	No.2DF	Rapeseed	30,100
	1990	Valmet	634 DS				30,100
	1990	Volvo	THD101GC				100
[503]	1992	Cummins	L10E	FTP, FTP Hot	No.2DF	Soy	20,30
[459]	1987	DDC	6V92TA	FTP	No.2DF	Soy	10,20,30,40
[460]	1991	Cummins	6BTA	FTP	No.2DF	Soy	100
[449]	1995	Cummins	B5.9	FTP	No.2DF	Rapeseed	20,50,100
[504]	1991	DDC	Series 60	FTP Hot	No.2DF	Soy	20
[505]	1988	DDC	6V92TA	FTP	No.2DF	Soy	20
[259]	1995	Cummins	B5.9	FTP Cold, FTP Hot	No.2DF	Soy	20, 100
	1997	Cummins	N14				
	1997	DDC	Series 50				
[506]	1997	Cummins	N14	FTP	No.2DF	Soy	100
[507]	1997	Caterpillar	3406E	FTP,FTP Hot	No.2DF	Soy	20,100
[131]	2000	Cummins	C8.3	FTP Hot	No.2DF	Canola, Yellow Grease, Tallow	5,20
	1998	Cummins	C8.3				
[461]	1987	DDC	6V92TA	FTP Hot	No.2DF	Soy, Canola	6,10,20,40
						Soy	20
[508]	1991	DDC	Series 60	FTP Hot	No.2DF	Soy	20
[509]	1987	Cummins	L10	FTP	No.2DF	Soy	20
	1987	DDC	6V92TA				
[224]	2006	Cummins	B5.9	HWY,FTP,WHTC,UDDS 28k,UDDS 6k,	ULSD	Soy	20,50
[130]	1996	IVECO	8360.46R	R49	No.2DF	Rapeseed	20
[510]	1991	DDC	6V-92TA-91	FTP Hot	No.2DF	Soy, Rapeseed	100

* Literature references identified in [square brackets]. Red font = 2-cycle engine. Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix VIIb. Literature Sources used to Assess Biodiesel Emissions Impacts: HD/MD Chassis Dynamometer Tests

Ref. No.*	Engine			Test Cycle	Base Fuel	Biodiesel Fuel	
	Year	Make	Model			Source	Blend Level
[130]	1996	IVECO	7.8	ECER49	No.2DF	Rapeseed	20
[486]	1989	Mack	E6	WVU5PK	No.2DF	Soy	35
	1992	Cummins	855				
	1989	Cummins	855				
	1993	DDC	Series 60				
	1994	DDC	Series 60				
[204]	2006	Cummins	10.7	FTP,UDDS	CARB	Soy, Tallow	20,50,100
[511]	1981	DDC	DDC8V71	Arterial, CBD, NY Comp	No.2DF	Soy	20
[512]	1988	DDC	6V92TA	Arterial, CBD, NY Comp	No.2DF	Soy	20
[126]	2004	International	D 285	CSHVC, RUCSBC	ULSD	Soy	20
	2006	International	DG 285	CSHVC, RUCSBC			
	2003	Cummins	ISB 300	CSHVC, UDDS			
	2000	DDC	Series 60	CSHVC, Freeway			
	2005	Cummins	ISM 330	CILCC, Freeway	No.2DF		
	2000	Cummins	ISM 280	CSHVC			
[513]	2006	Cummins	ISM	UDDS Cold, UDDS Hot	CARB, ULSD	Soy, Coconut	20
[514]	1994	Cummins	B5.9	Arterial, FTP	No.2DF	Rapeseed	20,50,100
{Peterson, 1993 PETERSON1994 /id}	1994	Cummins	Pickup	Transient	No.2DF	Rapeseed	20,50,100
[516]	1995	Cummins	B5.9	UDDS	No.2DF	Rapeseed	20,50,100
[186]	1994	Cummins	5.9L 6 CYL.	Arterial, FTP	No.2DF	Rapeseed	20,50,100
[517]	1994	Cummins	2500	UDDSH, UDDSC	No.2DF	Soy, Rapeseed, Safflower Coconut	20,100
[461]	1987	DDC	6V92TA	FTP Hot	No.2DF	Soy	20

* Literature references identified in [square brackets].   Red font = 2-cycle engine. Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix VIIc. Literature Sources used to Assess Biodiesel Emissions Impacts: LD Engine and Chassis Dynamometer Tests

Ref. No.*	Engine			Test Cycle	Base Fuel	Biodiesel Fuel	
	Year	Make	Model			Source	Blend Level
[445]	2004		EURO4	NEDC	ULSD	Rapeseed	30,50,100
[136]		Isuzu	4HF1	Custom	ULSD	Yellow Grease	20,40,60,80,100
[518]	1996	Dodge	2500	LD FTP	No.2DF	Soy	20,100
	1990	Dodge	250				
	1988	Ford	F250				
	1995	Ford	F350				
[124]	1990	GM	V8	LD FTP	CARB	Soy, Yellow Grease	20
	1989	GM	V8				
	1985	GM	V8				
	1987	GM	V8				
	1990	International	V8				
	1983	International	V8				
	1993	International	V8				
[511]	1988	Navistar	F-250	LD FTP	No.2DF	Soy	20,100
	1995	Navistar	F-350				
	1990	Chrysler	RAM 250				
	1996	Chrysler	RAM 2500				20,
[149]	1996	VW	Tdi	NEDC	ULSD	Soy	50,100
[168]	2001	Renault	Laguna	NEDC, Artem Mtw	ULSD	Palm, Rapeseed, Sunflower, Soy, Yellow Grease	10
[152]	2010	Subaru	2.0D XS	NEDC, Arterial Motorway	ULSD	Soy, Yellow Grease	20,30,50
[150]	2003	Toyota	2KD-FTV	NEDC, UDC	ULSD	Palm	5,20,40
[148]	1998	Toyota	TD	NDEC, UDC Hot, ADC	ULSD	Soy	5,10,20
[147]	1998	Toyota	TD	NDEC, UDC, ADC	ULSD	Rapeseed, Palm	5,10,20
[153]		Hyundai	2.2 VGT	NEDC	ULSD	Soy	10,30
[267]	2005	Hino	NO4C-TA	JE05	ULSD	Rapeseed	5,20,80,100
[144]				ESC	ULSD	Bioester	50,100
[429]		PSA DW 12A TED	PSA DW 12A TED	NDEC, UDC	ULSD	Palm, Rapeseed	10
[269]	2008	Toyota	2AD-FHV	NEDC	ULSD	Soy, Jatropha, Rapeseed	10,20,27,30,50,100
[143]			Phaser 180Ti	25% Load, 50% Load	ULSD	Yellow Grease	100
[146]	MODERN	Mitsubishi	4M40-2AT1	FTP	2008-DF	Yellow Grease	20
[519]	1998	DBENZ	OM611	custom	ULSD	Soy	20
[268]	2005	Toyota		EC	ULSD	Rapeseed	30

* Literature references identified in [square brackets].

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
Adept Group-1995	[483]	1987	DDC	6V92TA-83	N	FTP Hot	No.2DF	Rapeseed	6	-0.44	5.63	-7.36	-3.36	
									10	3.38	-13.56	-8.30	-14.29	
									20	1.51	-8.05	-6.60	-5.88	
									40	19.14	-37.99	-7.40	-22.76	
								Soy	20	-3.79	-13.98	2.47	-8.94	
									30	-2.15	-24.73	-2.09	-16.26	
									40	0.10	-31.90	-2.09	-22.76	
Alam-2004	[484]	2000	Cummins	B5.9	N	AVL 8	ULSD	Soy	20	-3.00	-20.00	9.38	-10.00	
							No.2DF			0.00	-17.65	-21.79	-9.09	
Bouche-2000	[485]	1990	John Deere	CD6068TL052 6081T	N	ISO-8178_C1	No.2DF No.2DF	Rapeseed	100	1.75	-38.46	10.00	-7.35	
										6.61	-66.22	8.68	-37.58	
Callahan-1993	[458]	1988	DDC	6V92TA	N	FTP	No.2DF	Soy	10	3.20	6.00	-4.76	-19.53	
						Custom				-4.80	-14.23	-2.94	-10.75	
						FTP				3.20	6.00	-4.76	-19.53	
						Custom				-4.12	0.22	-11.02	-3.53	
						FTP			20	7.42	-4.00	-9.52	-19.53	
						FTP				3.20	-9.43	4.17	-7.41	
						Custom				14.45	-19.57	-11.76	-13.46	
						Custom				-17.20	-66.45	-52.94	-67.08	
						FTP				7.42	-4.00	-9.52	-19.53	
						Custom				9.71	-2.44	-2.72	10.20	
						FTP				3.46	-9.43	4.17	-7.41	
						FTP			30	7.04	-11.32	0.00	-12.70	
						Custom				-2.97	-22.62	-11.76	-9.05	
						Custom				-2.33	-11.75	-8.44	-7.98	
						FTP				7.04	-11.32	0.00	-12.70	
						Custom			50	-6.10	-34.43	-2.94	-14.82	
						Custom			100	14.27	-45.49	*79.41*	-72.85	
Callahan-1993	[458]	1991	DDC	Series 60	N	FTP Hot	No.2DF	Soy	10	0.93	0.00	-4.35	-3.65	
									20	3.97	-7.14	-17.39	-7.76	
Clark-1999	[486]	1994	NAVISTAR	T444E	N	FTP Hot	No.2DF	Soy	20	1.67	-4.57	-59.28	-34.17	
									50	-0.10	-29.73	-31.58	-38.94	
									100	4.35	-61.36	-42.66	-48.86	
Colorado-1994	[487]	1991	DDC	Series 60	N	FTP	No.2DF	Soy	20	1.14	-2.13	-11.99	-3.45	-1.22
									35	0.97	-15.60	-27.05	-19.62	-0.02
									65	4.60	-35.46	-46.23	-31.65	0.19
									100	11.46	-43.97	-66.10	-47.07	2.08

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests (cont.)

Study ID	Ref. No.*	Year	Make	Model	Catalyst	Test Cycle	Base Fuel	Source	Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
Environment Canada-2005	[488]	1998	Caterpillar	3126E	N	FTP Hot	ULSD	Canola	20	-0.09	-15.98	-1.11	-6.89	-0.18
					Y					8.24		51.25	74.17	-6.52
Fosseen-1994	[491]	1988	DDC	6V92TA	N	ORTECH EPA	No.2DF	Soy	20	4.47	-38.10	-3.73	-16.20	1.03
									30	6.46	-40.48	-3.36	-21.76	0.74
Fosseen-1994b	[489]	1977	DDC	6V-71N	N	UDDS	No.2DF	Soy	20	2.21	-26.37	-2.28	-23.96	1.71
Fosseen-1994c	[491]	1989	DDC	6V92TA	N	FTP	No.2DF	Soy	20	4.47	-14.29	-3.73	-16.20	1.03
									20	3.51	-21.95	-6.59	-16.90	-1.31
									30	6.46	-30.95	-3.36	-21.76	0.74
Fosseen-1995	[490]	1977	DDC	6V-71N-77	Y	FTP	No.2DF	Soy	20	3.33	-9.52	4.40	-47.56	
					N				20	1.37	-13.95	14.54	-2.52	
Frank-2004	[492]	2001	International	DT466E	Y	FTP Hot	ULSD	Soy	20	-10.33	-20.00	-2.86	-37.86	-2.14
						FTP Cold				-9.04	-51.25	-6.67	-28.01	0.51
					N	FTP Hot				0.00	100.00	-16.67	-100.00	3.36
						FTP Cold				2.88	-50.00	-12.50	-40.93	5.72
						FTP Hot				1.83	-100.00	75.00	105.88	0.54
						FTP Cold				0.96		16.67	-30.77	0.85
Goetz-1993	[493]	1991	DDC	6V92TA	N	FTP Hot	No.2DF	Soy	20	4.88	-16.30	-20.81	-14.45	-0.07
						FTP		Soy	20	-3.40	13.51	19.14	7.82	-2.83
						FTP		Tallow	20	5.61	-20.00	-16.09	-10.78	0.15
Graboski-1996	[255]	1991	DDC	Series 60	N	FTP	No.2DF	Soy	20	1.14	-12.80	-13.67	-7.11	-0.36
									35	0.97	-9.76	-26.00	-17.72	-0.54
									65	4.60	-26.83	-45.00	-28.71	-0.72
									100	11.46	-43.90	-66.00	-46.99	1.99
Graboski-2000	{Graboski, 2003 GRABOSKI2000/id}	1991	DDC	Series 60	N	FTP Hot	No.2DF	Tallow	20	-2.34	-35.25	-23.82	-9.64	8.46
								Y. Grease	20	1.97	-12.31	-25.97	-6.61	4.80
								Soy	20	0.19	6.55	-28.66	-12.03	4.89
						FTP Cold		Canola	100	13.07	-40.74	-69.71	-40.82	-3.48
								Canola		10.32	-38.59	-70.29	-40.01	-0.27
						FTP Hot		Yellow Grease	100	4.99		-76.18	-47.03	-0.88
										5.60	-40.00	-74.14	-45.69	0.59
										7.20	-44.00	-75.86	-48.08	0.71
								Tallow	100	1.78	-35.84	-72.99	-45.73	-1.54
						FTP Cold		Lard	100	5.85	-28.89	-72.94	-43.08	-3.26
						FTP Hot				1.13	-35.84	-72.99	-50.57	2.25
						FTP Cold		Yellow Grease	100	3.29	-49.63	-75.59	-44.72	-3.65
						FTP Hot				4.38	-54.17	-72.99	-39.67	-0.62
						FTP Cold		Soy	100	15.22	-39.26	-72.65	-35.85	-1.81
						FTP Hot				13.50	-26.67	-69.14	-32.21	0.86
						FTP Cold		Tallow	100	0.49	-59.26	-77.65	-46.11	-4.34
						FTP Hot				0.91	-45.00	-72.99	-42.30	-1.54

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
Graboski-2003	[129]	1991	DDC	Series 60	N	FTP Hot	No.2DF	Soy	100	18.27	-26.67	-69.14	-30.80	1.57
Hansen-1997	[495]	1994	VOLVO	THD103KF	N	Steady state/ECER49	No.2DF	Rapeseed	100	22.91	-41.71	12.29	-12.56	
Knothe-2006	[218]	2003	DDC	S60	N	FTP Hot	No.2DF	Soy	100	12.33	-33.33	-77.98	-24.53	
Krahl-2008	[341]	2007	MAN	D08 36 LFL51	N	ESC	ULSD	Rapeseed	20	-4.37	0.00	-39.71	-23.40	
									100	17.46	-46.67	-54.41	-44.68	
		2000	Mercedes-Benz	OM 906 LA		ETC			5	0.33	-13.21	-25.93	-27.27	
									10	-1.95	-6.52	0.00	25.00	
									20	1.00	-4.65	0.00	10.00	
									30	3.95	-4.88	30.00	-18.18	
									40	1.90	-2.56	-3.85	22.22	
									100	6.21	-81.58	28.00	-9.09	
Krahl-2009	[341]	2000	Mercedes-Benz	OM 906 LA	N	ESC	ULSD	Rapeseed	100	18.75		-57.75	-54.55	
Lin-2009	[134]		Mitsubishi	6D14	N	ASTM	ULSD	Palm	20	-6.00	-22.86	-9.69	-4.91	-3.65
									100	-5.69	-15.30	21.11	1.05	-0.61
Liotta-1993	[497]	1991	DDC	Series 60	N	FTP Hot	No.2DF	Soy	5	0.65	-18.62	-4.40	-8.03	
Manicom-1993	[498]	1991	DDC	6V92TA	N	FTP	No.2DF	Soy	10	3.55	-12.50	-5.58	-5.30	0.46
									20	5.44	-22.22	-11.17	-12.58	0.46
									30	13.48	-25.00	-12.18	-24.50	4.74
									40	14.89	-40.28	-17.77	-29.14	4.59
Marshall-	[465]	1992	Cummins	L10E	N	FTP	No.2DF	Soy	20	3.20	-7.40	-12.40	-16.40	
									30	-7.90	-7.40	-4.80	-15.70	
McCormick-1997	[202]	1989	DDC	6V92TA	N	FTP Hot	No.2DF	Soy	8.9	2.29	0.66	-15.46	-6.92	
		1989	DDC	Series 60	N	FTP Hot	No.2DF	Soy	17.7	2.53	-10.21	-20.28	-14.44	
McCormick-2001	[213]	1991	DDC	Series 60	N	FTP Hot	No.2DF	Y. Grease	20	2.37	-42.33	-17.26	-11.10	-0.23
										-1.38	-53.50	-5.02	-4.26	-0.27
								Soy	20	2.82	-25.67	-17.96	-12.99	-0.44
										1.36	-38.50	-11.28	-3.87	-0.31
										1.56	-27.73	-21.88	-9.15	0.11
									50	5.53	-50.43	-46.34	-19.09	-0.94
						FTP		Y. Grease	100	4.50	-63.21	-62.56	-32.39	0.27
								Soy	100	12.42	-31.43	-66.93	-35.15	0.32
McCormick-2002	[256]	1991	DDC	Series 60	N	FTP	No.2DF	Soy	20	-7.00	-93.50	-21.77	4.00	
								Y. Grease	20	-7.38	-95.50	-16.13	1.21	
								Soy	100	-40.88	-94.00	-72.58	13.61	
								Y. Grease	100	-38.26	-98.00	-68.55	5.46	

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
McCormick-2005	[500]	2002	Cummins	B5.9	N	FTP Hot	ULSD	Soy	10	5.21	6.38	-14.77	-1.43	
								Tallow	20	2.79	-8.81	-18.37	-7.46	
		2003	DDC	Series 60				Tallow		1.74	-2.71	-23.00	-0.99	
		2002	Cummins	B5.9				Canola		2.30	-8.81	-20.77	-7.46	
		2003	DDC	Series 60				Soy + Tallow		3.16	-18.92	-26.16	-10.89	
		2002	Cummins	B5.9				Soy		3.27	-8.81	-25.57	-13.50	
		2003	DDC	Series 60				Soy		6.00	13.51	-24.05	0.99	
								Soy		6.00	-18.92	-21.94	-18.81	
								Soy		6.18	-8.81	-23.17	-8.47	
		2002	Cummins	B5.9				Soy		9.09	6.38	-25.57	-14.50	
								Soy		7.15	-8.81	-17.17	-15.51	
								Y. Grease		2.79	-8.81	-23.17	-12.49	
		2003	DDC	Series 60				Y. Grease		-0.63	-2.71	-23.00	-2.97	
								Soy	50	14.91	-8.81	-49.58	-24.56	
								Tallow	100	23.64	-39.21	-75.99	-46.69	
		2002	Cummins	B5.9				Canola		29.45	-39.21	-74.79	-43.67	
								Soy	100	34.79	-39.21	-75.99	-43.67	
								Soy		33.33	-24.01	-75.99	-36.63	
								Y. Grease		28.97	-39.21	-72.39	-46.69	
McDonald-1995	[385]	1983	Caterpillar	3304PCNA	N	ISO-8178_C1	No.2DF	Soy	30	2.08	-16.65		-6.36	
										2.93	0.00		0.00	
									100	-12.50	-25.03		-0.91	
					Y					-6.96	0.00		-17.16	
McGill-2003	[501]		International	7.31	N	AVL 8	No.2DF	Rapeseed	100	0.00		39.78		
Moser-2009	[178]	2002	Cummins	ISB	N	Custom	ULSD	Soy	20	5.05	4.35	-28.04	-11.59	
										4.73	-17.39	-22.43	-11.59	
Niper-1993	[499]	1991	Cummins	L10	N	Custom	No.2DF	Y. Grease	20	10.75	-4.35	-57.14	-29.41	
								Tallow	20	-0.16	-4.35	-14.29	-23.53	
								Tallow + Soy	30	4.83	-13.04	-28.57	-35.29	
								Y. Grease	100	17.29	-30.43	-14.29	-52.94	
								Tallow	100	10.90	-34.78	-28.57	-35.29	
Nuszkowski-2009	[261]	1999	Cummins	ISM 370	N	FTP	No.2DF	Soy	20	2.72	-16.15	-22.22	-15.03	-0.38
								Tallow	20	0.74	-18.08	-20.20	-13.67	-0.19
		2004						Soy	20	4.20	-11.85	-23.29	-9.85	0.00
								Tallow		2.52	-14.22	-27.40	-10.84	-0.50
Ortech-1995	[502]	1987	Cummins	N-14-87	N	FTP	No.2DF	Soy	10	2.06	-10.34	-10.30	0.00	
									20	3.16	-18.97	-14.91	-3.64	

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
Rantanen-1993	[448]	1990	Scania	DS9 52	N	R49	No.2DF	Rapeseed	30	3.76	0.00	-8.45	19.07	
									100	10.32	-39.95	21.13	7.73	
		1990	Valmet	634 DS	N	R49	No.2DF	Rapeseed	30	4.89	-20.11	-5.88	-12.56	
									100	21.55	-60.05	-24.37	-37.52	
		1990	Volvo	THD101GC	N	R49	No.2DF	Rapeseed	100	17.58	-16.74	-12.35	0.00	
Schumacher-1994	[459]	1987	DDC	6V92TA	Y	FTP	No.2DF	Soy	10	3.55	-12.50	-5.58	-5.30	0.46
									20	5.44	-22.22	-11.17	-12.58	0.46
									30	13.48	-25.00	-12.18	-24.50	4.74
									40	14.89	-40.28	-17.77	-29.14	4.59
Schumacher-1996	[460]	1991	Cummins	6BTA	N	FTP	No.2DF	Soy	100	10.97	-47.11	-13.32	-0.93	
Schumacher-2001	[503]	1992	Cummins	L10E	N	FTP	No.2DF	Soy	20	3.19	-7.41	-12.38	-16.44	
						FTP Hot				3.61	-7.41	-14.42	-14.69	
						FTP				-7.98	-7.41	-4.76	-15.75	
						FTP				-0.80	-3.70	-25.71	-23.29	
						FTP Hot				-1.40	-3.70	-25.96	-22.38	
						FTP Hot			30	1.20	-14.81	-33.65	-22.38	
						FTP				2.20	-11.11	-30.48	-26.03	
						FTP Hot				1.80	-11.11	-30.77	-25.87	
Sharp-1994	[505]	1988	DDC	6V92TA	N	FTP	No.2DF	Soy	20	4.81	-11.67	0.00	-13.13	
										2.08	-13.79	-14.29	-13.22	
		1991	DDC	Series 60	N	FTP Hot		Soy		-0.74	23.17	-8.94	-9.13	
										-1.08	30.43	-7.55	-9.24	
Sharp-1996	[449]	1995	Cummins	B5.9	N	FTP	No.2DF	Rapeseed	20	-1.71	-23.33	-6.10	-17.88	0.16
										1.18	-36.00	-8.22	-33.80	6.44
										0.11	-26.67	-12.68	-24.50	-0.64
										1.88	-40.00	-12.33	-31.69	1.65
									50	-2.85	-43.33	-13.62	-31.79	-0.16
										2.82	-52.00	-20.55	-47.89	5.12
										-1.94	-46.67	-18.31	-35.76	0.48
										1.18	-56.00	-24.66	-50.70	4.46
									100	-1.14	-63.33	-14.08	-33.44	4.10
										0.47	-72.00	-35.62	-54.93	7.43
										3.08	-70.00	-24.88	-40.40	3.22
										5.41	-76.00	-42.47	-57.04	5.61
Sharp-1998	[506]	1997	Cummins	N14	N	FTP	No.2DF	Soy	100	13.13	-95.65	-28.30	-45.33	
Sharp-2000	[259]	1995	Cummins	B5.9	N	FTP Cold	No.2DF	Soy	20	0.62	-26.32	-17.57	-18.53	
					N	FTP Hot				2.69	-34.43	-14.52	-22.65	
					Y	FTP Cold				1.01	-13.04	-4.71	-15.76	

Study ID	Ref. No.*	Engine Year	Engine Make	Engine Model	Catalyst	Test Cycle	Base Fuel	Biodiesel Source	Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
					Y	FTP Hot				3.62	-27.78	-11.33	-24.49	
					N	FTP Cold				1.45	-68.42	-32.43	-41.31	
					N	FTP Hot			100	4.59	-75.41	-38.58	-37.49	
					N	FTP Cold			100	1.65	-60.53	-38.51	-33.59	
					Y	FTP Cold				-1.22	-56.52	-42.35	-35.96	
					Y	FTP Hot				4.26	-69.44	-48.00	-42.18	
		1997	Cummins	N14	N	FTP Cold			20	0.20	-14.29	-7.56	-12.63	
					N	FTP Hot			20	3.77	-20.83	-4.48	-12.79	
					N	FTP Cold			100	9.88	-86.96	-30.09	-40.37	
					N	FTP Hot			100	14.29	-88.89	-27.20	-47.44	
		1997	DDC	Series 50	N	FTP Cold			20	8.43	0.00	-14.04	-5.18	
					N	FTP Hot			20	2.23	0.00	-14.85	-3.57	
					Y	FTP Cold			20	9.61	25.00	-23.53	-4.95	
					Y	FTP Hot			20	1.78	100.00	-19.58	-14.23	
					N	FTP Cold			100	21.06	-71.43	-46.49	-34.72	
					N	FTP Hot			100	9.82	-81.82	-49.75	-38.04	
					N	FTP Cold			100	12.64	-57.14	-46.49	-34.72	
					Y	FTP Cold			100	11.35	-25.00	-52.94	-58.24	
					Y	FTP Hot			100	8.91	-50.00	-58.74	-43.82	
Smith-1998	[507]	1997	Caterpillar	3406E	N	FTP Hot	No.2DF	Soy	20	2.86	-20.00	-6.49	-13.70	-0.45
						FTP			20	3.52	-23.33	0.00	-7.53	0.09
									100	17.21	-61.58	-48.05	-50.21	0.83
Souligny-2004	[131]	1998	Cummins	C8.3	N	FTP Hot	No.2DF	Y. Grease	5	0.00	5.26	-10.33	-10.00	0.20
								Canola	20	1.37	-10.53	-30.79	-30.00	-0.87
								Tallow	20	-1.37	-10.53	-22.21	-20.00	-0.95
								Y. Grease	20	0.00	-5.26	-19.52	-30.00	-1.88
		2000	Cummins	C8.3	N			Canola	5	-2.08	-17.65	0.75	-16.67	1.28
								Y. Grease	5	-4.17	-5.88	-1.49	-16.67	-0.42
								Tallow	5	-4.17	-11.76	-2.99	-16.67	-1.33
								Canola	20	0.00	-23.53	-16.67	-33.33	1.08
								Y. Grease	20	-6.25	-23.53	-13.93	-33.33	-0.35
								Tallow	20	-4.17	-29.41	-7.96	-16.67	0.76
Spataru-1995	[461]	1987	DDC	6V92TA	N	FTP Hot	No.2DF	Canola	6	11.98	-8.96	-6.26	0.81	-1.96
								Canola	6	1.78	-5.52	-7.92	-10.92	-0.15
								Canola	10	3.38	-13.56	-8.30	-14.29	-0.61
								Canola	20	13.41	-21.68	-2.47	-2.44	-1.36
								Canola	20	4.45	-16.55	-10.19	-12.61	-0.15
								Soy	30	-2.15	-24.73	-2.09	-16.26	3.93
								Soy	40	0.10	-31.90	-2.09	-22.76	3.63
								Canola	40	19.14	-37.99	-7.40	-22.76	-1.66
								Soy	20	-3.79	-13.98	2.47	-8.94	3.93

Appendix VIIIa. Emissions Impacts of Biodiesel Usage: HD/MD Engine Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
Starr-1997	[508]	1991	DDC	Series 60	N	FTP Hot	No.2DF	Soy	20	-4.42	-66.61	-16.96	-21.47	
Stotler-1995	[509]	1987	DDC	6V92TA	N	FTP	No.2DF	Soy	20	3.16	-11.27	-4.41	-9.29	
		1987	Cummins	L10				Soy		2.48	-7.87	-8.41	-15.88	
Sze-2007	[224]	2006	Cummins	B5.9	Y	HWY	ULSD	Soy	20	6.69	-5.56	-32.20	-20.34	0.38
						FTP				4.21	-5.56	-38.05	-12.93	0.06
						WHTC				4.55	-11.54	-32.98	-18.68	0.18
						UDDS 28k				3.51	6.90	-26.03	-9.83	0.06
						UDDS 6k				1.15	-0.67		-6.74	1.06
						HWY			50	17.15	-38.89	-61.02	-38.98	-0.06
						FTP				13.43	-38.89	-57.52	-29.25	0.47
						UDDS 28k				11.82	-18.97	-57.53	-27.17	0.28
						UDDS 6k				2.13	-31.54		-18.06	0.23
Turrio-Baldassari-2003	[130]	1996	IVECO	8360.46R	N	R49	No.2DF	Rapeseed	20					
Winsor-1993	[510]	1991	DDC	6V-92TA-91	N	FTP Hot	No.2DF	Rapeseed	100	15.91	-79.55	-27.75	-46.36	
								Soy		19.63	-72.73	-33.04	-42.38	

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption   Blue font = Emissions data considered an outlier
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix VIIIb. Emissions Impacts of Biodiesel Usage: HD/MD Chassis Dynamometer Tests

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
Baldassarri-2004	[130]	1996	IVECO	7.8	N	ECER49	No.2DF	Rapeseed	20	0.00	-16.67	3.85	-9.52	
Clark-1999	[520]	1989	Mack	E6	N	WVU5PK	No.2DF	Soy	35	8.94	-2.47	13.98	8.21	
										5.54	9.30	4.95	-22.25	
			Cummins	855						12.86	-19.43	-26.19	-2.66	
										-14.34	-19.13	-28.00	-2.40	
		1992	Cummins	855						12.89	-7.38	0.00	-7.98	
		1993	DDC	Series 60						12.28	-7.14	-21.05	-14.69	
		1994	DDC	SERIES 60						-5.74	-27.78	-33.33	-40.65	
										0.00	-16.67	-11.11	-20.36	
Durbin-1981	[511]	1981	DDC	DDC8V71	N	CBD	No.2DF	Soy	20	11.30	-31.62	-28.26	-17.15	-2.51
						Arterial				24.53	-33.85	-16.44	-21.57	-1.27
						NY Comp				-10.65	-8.64	42.31	-14.95	2.04
Durbin-2009	[204]	2006	Cummins	10.7	N	UDDS	CARB	Soy	20	3.39	-13.94	-23.08	4.55	0.60
						UDDS		Tallow		-1.67	-15.00	-9.38	-12.20	-0.24
						FTP		Soy		5.00	-9.68	-23.75	-2.67	0.32
						FTP		Tallow		5.00	-3.33	-11.54	-1.41	-0.79
						FTP		Tallow		0.00	-10.00	-21.79	-4.23	0.00
						UDDS		Soy	50	6.78	-27.27	-29.23	20.45	2.41
						UDDS		Tallow		0.00	-38.75	-23.44	-14.63	0.95
						FTP		Soy		10.00	-32.26	-47.50	-2.67	0.48
						FTP		Tallow		5.00	-35.00	-44.87	-8.45	0.32
						UDDS		Soy	100	16.95	-53.94	-32.31	55.45	4.22
						UDDS		Tallow		1.67	-73.75	-31.25	-18.05	2.14
						FTP		Soy		25.00	-64.52	-58.75	0.00	0.80
						FTP		Tallow		10.00	-70.00	-64.10	-29.58	0.79
Howes-1988	[512]	1988	DDC	6V92TA	N	CBD	No.2DF	Soy	20	-0.34	-0.67	9.56	10.56	-1.15
						Arterial				8.98	-16.28	-11.97	-11.22	74.09
						NY Comp				-1.02	-3.50	12.31	22.75	0.55

* Literature references identified in [square brackets].

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Appendix VIIIb. Emissions Impacts of Biodiesel Usage: HD/MD Chassis Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine Year	Engine Make	Engine Model	Catalyst	Test Cycle	Base Fuel	Biodiesel Source	Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
McCormick-2006	[126]	2004	International	D 285	Y	RUCSBC	ULSD	Soy	20	6.23	-19.66	-24.01	-22.60	-0.21
						CSHVC				-0.68	-1.14	2.49	9.57	0.16
		2006	International	DG 285	N	RUCSBC				2.35	-8.40	21.43	-42.31	0.03
						CSHVC				-0.83	42.15	33.33	-17.15	0.62
		2003	Cummins	ISB 300		CSHVC				2.75	-13.84	-28.09	-22.36	-0.40
						UDDS				3.39	-3.62	-29.95	-19.20	-0.49
		2000	DDC	Series 60		CSHVC				2.06	-15.20	-19.35	-10.67	0.56
						Freeway				3.62	-16.02	-26.17	-6.92	0.27
		2005	Cummins	ISM 330		CILCC				-0.09	-16.67	-27.23	-15.34	-1.05
						Freeway	No.2DF			2.37	-12.33	-34.72	-14.71	-1.18
		2000	Cummins	ISM 280		CSHVC				-2.68	-19.97	-17.15	-12.00	-0.45
						CSHVC				-5.82	-28.24	-17.34	-26.83	-1.22
						CSHVC				-3.94	-28.02	-33.02	-20.33	0.80
						CSHVC				-3.74	-28.09	-20.53	-18.58	0.58
Nikanjam-2009	[513]	2006	Cummins	ISM	N	UDDS	ULSD	Soy	20	8.94	-57.58		60.42	
						Cold	CARB			3.92	-2.80		736.00	
						UDDS	ULSD			1.31	-28.30			
						Hot	CARB			1.48	56.52			
Peterson-1994a	[514]	1994	Cummins	B5.9	N	Arterial	No.2DF	Rapeseed	20	-2.62	-20.17	-10.35	-25.26	-0.01
						FTP			20	-4.13	-18.03	-7.57	-31.27	1.60
						Arterial			50	-5.27	-37.21	7.66	-39.14	0.70
						Arterial			100	-9.12	-55.58	6.76	-42.19	0.69
						FTP			100	-7.58	-49.55	21.26	-53.96	0.71
Peterson-1994b	{Peterson, 1993 PETERSON1994/id}	1994	Cummins	Pickup	N	Transient	No.2DF	Rapeseed	20	-4.59	-18.45	-2.78	-30.08	0.74
									50	-7.96	-33.01	11.11	-45.65	0.59
									100	-11.49	-54.37	8.33	-48.81	1.19
Peterson-1996	[186]	1995	Cummins	5.9L 6 CYL.		FTP	No.2DF		20	-7.51	-16.63	5.98	-17.65	-3.43
									100	-12.36	-62.06	43.48	-34.75	-2.20
									50	-2.92	-43.44	35.33	-34.84	2.62
		1994	Cummins	5.9L 6 CYL.	N	FTP	No.2DF	Rapeseed	20	-5.99	-18.58	-6.08	-35.07	1.37
						Arterial	No.2DF			-4.02	-19.68	-4.93	-27.59	0.29
						FTP	No.2DF			-3.64	-20.13	-14.07	-31.76	1.47
						FTP	No.2DF		50	-7.88	-33.49	4.14	-50.41	-0.04
						Arterial	No.2DF			-8.19	-35.00	12.25	-43.75	0.81
						FTP	No.2DF		100	-12.22	-52.79	16.79	-53.15	1.20
						Arterial	No.2DF			-11.25	-60.04	1.31	-47.04	0.99
						FTP	No.2DF			-7.83	-48.16	24.03	-53.66	7.48

* Literature references identified in [square brackets].

Appendix VIIIb. Emissions Impacts of Biodiesel Usage: HD/MD Chassis Dynamometer Tests (cont.)

Study ID	Ref. No.*	Year	Make	Model	Catalyst	Test Cycle	Base Fuel	Source	Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
Peterson-1999	[516]	1995	Cummins	B5.9	N	UDDS	No.2DF	Rapeseed	20	-5.01	-19.22	3.37	-22.30	-1.29
					Y				20	-4.34	-12.14	28.28	-16.89	0.97
					N				50	-5.32	-39.60	34.55	-35.01	1.60
					Y				50	-7.83	-33.91	33.33	-32.59	-0.55
					N				100	-10.15	-62.62	38.48	-39.32	-0.73
					Y				100	-8.87	-62.53	18.69	-39.58	0.96
Peterson-2000	[517]	1994	Cummins	2500	N	UDDSH	No.2DF	Coconut	20	-12.58	-22.97	-12.74	-28.18	-9.22
								Soy	20	-5.79	-29.80	6.37	-36.09	-2.08
								Rapeseed	20	-3.07	-36.38	-11.46	-36.46	-4.62
								Soy	20	-5.03	-9.39	4.46	-14.34	-8.66
								Coconut	100	-23.17	-54.06	-26.11	-52.56	-2.87
								Soy	100	-17.53	-66.52	54.78	-56.07	-4.80
								Soy	100	-14.67	-85.01	-67.01	-64.59	4.33
								Mustard	100	-3.02	-59.09	70.06	-51.13	-0.15
								Rapeseed	100	-11.07	-74.89	14.65	-52.78	-5.50
						UDDSC		Rapeseed	100	-8.52	-85.74	-68.56	-59.68	-0.76
						UDDSH		Safflower		0.62	-49.79	70.70	-31.85	-2.26
								Soy		-0.84	-46.03	56.69	-27.63	-19.83
						UDDSC		Soy		-1.58	-58.15	-8.56	-24.89	3.00
Spataru-1995	[461]	1987	DDC	6V92TA	N	CBD	No.2DF	Soy	20	4.50	-16.70	-6.10	-20.20	-0.20

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption   Blue font = Emissions data considered an outlier
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix VIIIc. Emissions Impacts of Biodiesel Usage: LD Engine and Chassis Dynamometer Tests

Study ID	Ref. No.*	Engine Year	Engine Make	Engine Model	Catalyst	Test Cycle	Base Fuel	Biodiesel Source	Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
Bielaczyc-2009	[445]	2004		EURO4	Y	NEDC	ULSD	Rapeseed	30	8.36	-3.00	-21.00	5.26	1.63
									50	9.09	55.00	-11.00	57.89	1.63
									100	9.09	203	338.00	148.00	1.63
Durbin-1999	[511]	1988	Navistar	F-250	N	LD FTP	No.2DF	Soy	20	0.38	-8.49	13.74	-5.47	
									100	10.74	-5.89	23.04	-12.05	
		1990	Chrysler	Ram 250					20	-2.16	19.44	142.17	4.85	
									100	8.84	-20.70	328.59	8.45	
		1995	Navistar	F-350	Y				20	-3.66	-20.41	32.55	-15.04	
									100	1.42	-66.64	43.29	-22.88	
		1996	Chrysler	Ram 250					20	-2.05	-21.07	-17.07	-7.88	
									100	-2.18	-39.34	-10.10	-6.87	
Durbin-2000	[518]	1988	Ford	F250	N	LD FTP	No.2DF	Soy	100	11.11	-2.86	13.71	-13.10	
									20	1.59	-5.71	17.01	-4.83	
		1990	Dodge	250					100	9.38	-17.39	382.03	8.65	
									20	-3.13	23.91	151.91	6.73	
		1995	Ford	F350	Y				20	-4.76	-18.03	40.18	-17.78	
									100	1.59	-63.93	38.23	-23.56	
		1996	Dodge	2500					100	-1.19	-33.33	-14.05	-5.84	
									20	-1.19	-16.67	-28.92	-8.44	
Durbin-2001	[124]	1983	International	V8	N	LD FTP	CARB	Soy	20	6.04	-2.39	31.08	-2.92	
								Y. Grease		4.83	-28.13	-6.68	-28.95	
		1985	GM	V8				Soy		1.04	0.86	48.48	-7.43	
								Soy		8.50	-7.98	-10.52	-2.12	
								Y. Grease		3.36	-20.65	-6.47	-12.63	
								Soy		8.83	-11.35	-12.11	-1.57	
		1987	GM	V8				Soy		1.80	8.99	16.00	-2.43	
								Soy		1.53	22.57	14.13	-0.10	
								Y. Grease		0.60	-34.36	-7.45	-29.80	
		1989	GM	V8				Soy		1.16	41.65	22.93	13.94	
								Soy		5.16	40.12	21.28	10.10	
								Y. Grease		4.62	13.06	15.90	-0.33	
		1990	GM	V8				Soy		4.54	-24.26	-2.86	-9.43	
								Y. Grease		4.87	-66.36	-3.59	-46.03	
								Soy		1.96	-41.76	-2.10	-11.74	
			International	V8				Y. Grease		-4.97	17.78	0.99	-10.71	
								Soy		2.34	16.11	-8.25	-1.20	
								Soy		2.81	62.22	-7.82	0.34	

Appendix VIIIc. Emissions Impacts of Biodiesel Usage: LD Engine and Chassis Dynamometer Tests (cont.)

Study ID	Ref. No.*	Engine Year	Engine Make	Engine Model	Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel Source	Biodiesel Fuel Blend Level	NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		1993	International	V8				Y. Grease		8.74	-47.42	-19.79	-27.62	
		1993	International	V8				Soy		-0.87	-23.65	12.99	-5.79	
		1993	International	V8				Soy		2.23	-18.91	21.55	-6.51	
Fontaras-2009	[149]	1996	VW	Tdi	Y	NEDC	ULSD	Soy	50	-1.82	36.36	4.17	66.67	6.38
									100	5.45	63.64	83.33	118.75	9.93
Fontaras-2010	[168]	2001	Renault	Laguna	Y	NEDC	ULSD	Palm	10	-1.00	38.00	-16.00		-4.00
						NEDC		Rapeseed		0.00	15.00	-30.00		0.00
						NEDC		Sunflower		4.00	18.00	-14.00		4.00
						NEDC		Soy		-4.00	20.00	-27.00		-2.00
						NEDC		Y. Grease		-4.00	60.00	-10.00		0.00
						Artem Mtw		Palm		20.00	2.00	-12.00		2.00
						Artem Mtw		Rapeseed		-4.00	20.00	4.00		0.00
						Artem Mtw		Sunflower		24.00	42.00	-4.00		4.00
						Artem Mtw		Soy		-12.00	-18.00	-32.00		-4.00
						Artem Mtw		Y. Grease		-16.00	-25.00	-26.00		-5.00
Karavalakis-2009a	[148]	1998	Toyota	TD	N	UDC Hot	ULSD	Soy	5	2.08	-7.41	-4.17	-2.02	-0.57
						ADC				4.26	-3.45	-7.69	-2.91	0.41
						NDEC			10	3.57	-13.51	-23.53	-3.28	-3.23
						UDC Hot				4.17	-18.52	-8.33	-4.04	-1.14
						ADC				10.64	-6.90	-11.54	13.59	0.00
						NDEC			20	0.00	-18.92	-23.53	-4.92	-3.23
						UDC Hot				5.21	-25.93	-4.17	-5.05	-0.57
						ADC				11.49	-20.69	-23.08	12.62	-6.12
Karavalakis-2009b	[150]	2003	Toyota	2KD-FTV	Y	NEDC	ULSD	Palm	5	-2.00	20.00	42.86	-6.15	0.00
						UDC				1.32	5.00	7.69	-1.41	0.00
						NEDC			20	12.00	26.67	14.29	7.69	7.36
						UDC				10.53	12.50	-23.08	5.63	1.60
						NEDC			40	-4.00	0.00	0.00	4.62	0.00
						UDC				3.95	9.00	-30.77	7.04	2.67
Karavalakis-2009c	[147]	1998	Toyota	TD	N	NDEC	ULSD	Rapeseed	5	7.07	-16.22	-6.79	-5.84	-3.23
						NDEC		Soy		1.79	-8.11	-17.65	-0.98	-1.29
						NDEC		Palm		-2.87	-9.68	-9.09	-6.67	-3.23
						UDC		Rapeseed		-0.72	-2.54	-8.99	-1.25	-4.76
						UDC		Palm		-1.43	0.00	-11.76	-1.25	-4.76
						ADC		Rapeseed		-1.11	-3.86	-2.24	0.81	-0.41
						ADC		Palm		-1.11	1.89	6.67	1.63	1.22
						NDEC		Rapeseed	10	7.07	-9.80	-9.05	-10.00	-7.10
						NDEC		Palm		-2.87	-3.23	-9.09	-13.33	-9.68
						UDC		Rapeseed		-4.29	-13.01	-11.91	-3.75	-11.90

Study ID	Ref. No.*	Engine			Catalyst	Test Cycle	Base Fuel	Biodiesel Fuel		NOx % Change	HC % Change	PM % Change	CO % Change	CO2 % Change
		Year	Make	Model				Source	Blend Level					
								Palm		-8.57	-10.53	-17.65	-3.75	-14.29
						ADC		Rapeseed		-3.33	-7.62	-0.03	-1.02	-2.45
								Palm		-6.67	-1.89	11.11	-2.04	-2.86
						NDEC		Rapeseed		14.78	-25.84	15.80	-2.51	-0.97
								Palm		12.58	3.23	18.18	-6.67	-1.29
						UDC		Rapeseed	20	-2.85	-30.34	-11.91	-4.37	-2.38
								Palm		-5.71	-21.05	-11.76	-3.75	0.00
						ADC		Rapeseed		-1.11	-16.99	8.81	1.52	-1.02
								Palm		-2.22	-5.66	20.00	-2.04	1.22
Kawano-2008	[267]	2005	Hino	NO4C-TA	Y	JE05	ULSD	Rapeseed	5	7.14	-80.56	-9.09	5.71	
									20	28.57	-81.00	-27.27	-17.14	
									80	100.00	-90.00	10.91	-31.43	
									100	135.71	-96.67	23.64	-31.43	
Kousoulidou-2009	[429]		PSA DW 12A TED	PSA DW 12A TED	Y	NDEC	ULSD	Palm		0.00	34.09	-16.46	20.00	
								Rapeseed	10	6.38	11.36	-30.38	12.00	
								Palm		15.79	41.18	-20.34	-25.00	
								Rapeseed		-5.26	5.88	-27.12	100.00	
Lance-2009	[269]	2008	Toyota	2AD-FHV	Y	NEDC	ULSD	Rapeseed	10	25.00	-25.00		-2.27	-1.14
								Soy		8.00	-34.38		0.00	-1.82
								Rapeseed	20	28.57	-2.50		0.00	-0.28
								Jatropha		21.43	-32.50		-11.36	-0.85
								Jatropha	27	-4.00	-56.25		-3.66	-5.45
									30	42.86	-12.50		31.82	-0.17
								Rapeseed	50	21.43	-20.00		40.91	0.28
									100	60.71	0.00		86.36	3.13
Peng-2008	[146]	MODERN	Mitsubishi	4M40-2AT1	N	FTP	ULSD	Y. Grease	20					
Sirman-1998	[519]	1998	DBENZ	OM611	N	Custom	ULSD	Soy	20	2.58	35.55	-14.46	-4.98	-0.98
Yoshida-2008	[268]	2005	Toyota		Y	EC	ULSD	Rapeseed	30	-4.76	-28.00	-16.67	-16.48	
					N					0.00	-8.00	-21.05	-3.03	

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption   Blue font = Emissions data considered an outlier
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix IXa. Impacts of Biodiesel Usage upon Aldehyde Emissions: HD Engine Tests

Study ID No.	Ref. No.*	Engine Make	Engine Model	Engine Year	After treat ment	Test Cycle	Biodiesel Feedstock	Blend Level	Aldehyde Analysis Method	Formal. % Change	Acetal. % Change	Acrolein % Change	Total Carbonyls % Change
Callahan-93	[458]	DDC	Series 60	1991	N	FTP	Soy	10	DNPH Crt.				11.83
								20					-10.69
Graboski-2000	{Graboski, 2003 GRABOSKI2000/id}	DDC	Series 60	1991	N	FTP	Soy	100	DNPH Crt.	-47.19	-13.99		13.50
							Canola			-47.19	-44.62		-7.00
						FTP Hot	Tallow			70.79	-59.42		7.00
Howes	[512]	DDC	6V92TA	1988	N	CBD	Soy	20	DNPH Crt.	-4.47			
						Arterial				10.51			
						NY Comp				1.15			
Lin-2009	[134]	Mitsubishi	6D14		N	ASTM	Palm	20	DNPH Crt.	7.11	33.69	10.19	
								100		15.56	67.79	31.48	
McDonald-1995	[385]	Caterpillar	3304 PCNA		N	ISO-8 Mode	Soy	30	FTIR	8.33			
								100		8.33			
					Oxid			30		25.00			
								100		41.67			
Rantanen-1993	[448]	Valmet	634 DS	1990	N	R49-mode 6	Rapeseed	30	FTIR	0.00			
										0.00			
								100		16.67			
										28.57			
										46.15			
		VOLVO	THD101GC	1990						0.00			
										-40.00			
Sharp-1998	[506]	Cummins	N14	1997	N	FTP	Soy	100	DNPH Imp.	47.30	-48.14	-42.17	
Souligny-2004	[131]	Cummins	C8.3	2000	N	FTP	YG	5	DNPH Crt.				-8.06
							Soy						-8.06
							Tallow						-9.68
							YG	20					-30.65
							Soy						-11.29
							Tallow						-25.81
Turrio-Baldassarri-2003	[130]	IVECO	8360.46R		N	R49	Rapeseed	20	DNPH Crt.	18.50	6.33	105.18	

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix IXb. Impacts of Biodiesel Usage upon Aldehyde Emissions: LD Engine Tests

Study ID No.	Ref. No.*	Engine Make	Engine Model	Engine Year	After-treatment	Test Cycle	Biodiesel Feedstock	Blend Level	Aldehyde Analysis Method	Formal. % Change	Acetal. % Change	Acrolein % Change	Total Carbonyls % Change
Di-2008	[521]	Isuzu	4HF1		N	Custom	YG	20	IMR mass spec	-1.02	20.00		
								40		-18.37	49.33		
								60		-21.43	52.00		
								80		-27.55	52.00		
								100		-43.88	46.67		
Fisher-2010	[145]	John Deere	4024T	2003	N	50% Load	Soy	20	FTIR	-5.56	-4.00		
							Canola	20		-5.93	-4.00		
							Algae	20		-0.93	6.67		
							Algae	20		-1.85	0.00		
							Soy	100		-16.67	-22.67		
							Canola	100		-20.37	-20.00		
							Algae	100		-11.11	-20.00		
							Algae	100		-2.78	-19.73		
						75% Load	Soy	20		-11.00	-13.62		
							Canola	20		-5.00	-16.94		
							Algae	20		12.00	-6.98		
							Algae	20		12.00	-8.64		
							Soy	100		-14.00	-25.25		
							Canola	100		-2.00	-17.61		
							Algae	100		16.00	-13.62		
							Algae	100		12.00	-21.93		
Koszalka-2010	[144]	None given			N	ESC	Bioester (trade name)	50	FTIR	-18.18	4.55		
								100		-33.33	2.22		
Lea-Langton-2009	[143]	Perkins	Phaser 180Ti		N	25% Load	YG	100	FTIR	4.00	20.00	-50.00	
					Oxid					15.00	-55.56	-55.56	
					N	50% Load				40.00	-42.50	-83.33	
					Oxid					14.29	-75.00	-60.00	
Yu-Yin-2009	[139]	None given	QC495	2003	N	Custom	Palm	10	DNPH Crt.	-21.89	57.98	9.45	21.51
								30		69.59	-16.58	247.26	34.05
								50		177.06	130.04	235.32	169.62
								75		166.71	-8.05	278.61	72.25
								100		178.51	12.25	527.86	105.91

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix IXc. Impacts of Biodiesel Usage upon Aldehyde Emissions: LD Chassis Tests

Study ID No.	Ref. No.*	Engine Make	Engine Model	Engine Year	After-treatment	Test Cycle	Biodiesel Feedstock	Blend Level	Aldehyde Analysis Method	Formal. % Change	Acetal. % Change	Acrolein % Change	Total Carbonyls % Change
Durbin-1999	[511]	Chrysler	Ram 250	1990	N	FTP Light Duty	Soy	100	DNPH Crt.	27.64	20.41	-47.02	
								20		9.81	64.71	47.63	
		Navistar	F-250	1988				100		13.73	10.32	-9.73	
								20		1.10	3.83	13.27	
Fontaras-2009	[149]	VW	Tdi	1996	Oxid	NEDC	Soy	100	DNPH Crt.	622.04	1725.37	1334.03	
Fontaras-2010	[168]	Renault	1.9 dCi		Oxid	NEDC	Palm	10	DNPH Crt.				45.70
							Rapeseed						78.81
							Sunflower						0.00
							YG						-66.89
							Soy						-63.58
						Art. Motorway	Palm						78.95
							Rape						110.53
							Sunflower						21.05
							YG						-65.79
							Soy						-49.47
Hasegawa-2007	[436]	Isuzu	4H-L1	2003	N	JE08	Soy	100	DNPH Crt.	47.50	71.43		
							Rapeseed			10.00	35.71		
							Palm			5.00	71.43		
							Soy			47.06	28.57		
							Rapeseed			5.88	0.00		
							Palm			0.00	-21.43		
Karavalakis-2009a	[148]	Toyota	TD	1998	N	NEDC	Rapeseed	5	DNPH Crt.	48.22	-0.01	-14.58	
								10		123.21	-43.58	-81.25	
								20		148.22	-57.70	94.79	
							Palm	5		17.07	-13.58	BDL	
								10		53.66	-53.09	BDL	
								20		63.41	-64.20	BDL	
						ADC	Rapeseed	5		-28.57	560.00	-7.27	
								10		269.05	1740.00	-18.18	
								20		350.00	2150.00	-22.42	
							Palm	5		15.69	-3.92	BDL	
								10		23.53	-23.53	BDL	
								20		52.94	-31.37	BDL	
Karavalakis-2009b	[150]	Toyota	2KD-FTV	2003	Oxid	NEDC	Palm	5	DNPH Crt.	-4.25	-42.00		
								10		-4.34	-20.08		
								20		-30.82	-6.81		
Karavalakis-2009c	[150]	Toyota	TD	1998	N	NEDC	Soy	5	DNPH Crt.	-20.18	-21.68	2.74	
								10		-32.60	-33.57	BDL	

Appendix IXc. Impacts of Biodiesel Usage upon Aldehyde Emissions: LD Chassis Tests (cont.)

Study ID No.	Ref. No.*	Engine Make	Engine Model	Engine Year	After-treatment	Test Cycle	Biodiesel Feedstock	Blend Level	Aldehyde Analysis Method	Formal. % Change	Acetal. % Change	Acrolein % Change	Total Carbonyls % Change
								20		-46.78	-82.87	BDL	
						ADC		5		-30.27	6.02	-4.76	
								10		-40.99	-45.03	BDL	
								20		-60.81	-58.64	BDL	
Karavalakis-2010b	[150]	Hyundai	2.2 VGT		Oxid	NEDC	Soy	10	DNPH Crt.	4.36	4.64	-23.08	
								30		5.26	10.82	20.09	
Karavalakis-2010	[153]	Subaru	2.0D XS	2007	Oxid/DPF	NEDC	Soy	20	DNPH Crt.				3.54
								30					7.96
								50					22.12
							YG	20					7.96
								30					14.16
								50					42.48
						Art. Motorway	Soy	20					7.14
								30					21.43
								50					35.71
							YG	20					21.43
								30					31.43
								50					57.14
Peng-2008	[146]	Mitsubishi	4M40-2AT1	Modern	N	FTP	YG	20	DNPH Crt.	-23.08	16.92	16.67	-15.92

* Literature references identified in [square brackets].   Red font = 2-cycle engine   Green font = Assumption
Blue shading indicates tests excluded from data analysis because of failure to satisfy engine selection criteria.

Appendix X. Literature Sources Consulted for LCA Assessments of Biodiesel and Renewable Diesel

Study No.	Ref. No.	Year	in Data Base	Citation
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15	[533]	2005		SentemNovem. Participative LCA on Biofuels. Rapport 2GAVE-05.08. 2005. The Hague, Netherlands, Sentem Novem.
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Appendix X. Literature Sources Consulted for LCA Assessments of Biodiesel and Renewable Diesel (cont.)

Study No.	Ref. No.	Year	in Data Base	Citation
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Appendix X. Literature Sources Consulted for LCA Assessments of Biodiesel and Renewable Diesel (cont.)

Study No.	Ref. No.	Year	in Data Base	Citation
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64	[569]	2008	X	Jin H and Nelson R: Life Cycle Assessment of Tallow-Based Renewable Diesel Fuel. #542a(2008).
65	[570]	2008	X	Kalnes T, Marker T, Shonnard D, and Koers K: Green diesel production by hydrorefining renewable feedstocks. Biofuels-Q4(2008). www.biofuels-tech.com
66	[284]	2008		Keeney, R. and Hertel, T. The Indirect Land Use Impacts of U.S. Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses. 2008. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. GTAP Working Papers.
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Study No.	Ref. No.	Year	in Data Base	Citation
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69	[573]	2008		Mbarawa M: Performance, emission and economic assessment of clove stem oil-diesel blended fuels as alternative fuels for diesel engines. Renewable Energy, 33(5), 871-882 (2008).
70	[574]	2008	X	Nikander S: Greenhouse Gas and Energy Intensity Assessment of Product Chain Case Transport Biofuel. M.S. Thesis(Department of Civil and Environmental Engineering, Helsinki University of Technology), 1-88 (2008).
71	[305]	2008		Panichelli, L and Gnansounou, E. Estimating greenhouse gas emissions from indirect land-use change in biofuels production: concepts and exploratory analysis for soybean-based biodiesel production. BPE-ENAC-EPFL. 2008. Bioenergy and Energy Planning Group.
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74	[310]	2008	X	Reijnders, L. and M. A. J. Huijbregts. "Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans." Journal of Cleaner Production 16.18 (2008): 1943-48.
75	[577]	2008	X	Rettenmaier, N., Koppen, S., Gartner, S., and Reinhardt, G. Screening Life Cycle Assessment of Hydrotreated Jatropha Oil. 2008. IFEU.
76	[578]	2008		Riley, C and Sandor, D. Transitioning to Biofuels: A system-of-systems Perspective. NREL/CP-150-42990. 6-19-2008.
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85	[583]	2009		S&T2 Consultants Inc. GHG Emission Reductions From World Biofuel Production and Use. 11-23-2009. Global Renewable Fuels Alliance.
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Study No.	Ref. No.	Year	in Data Base	Citation
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94	[588]	2009		Dumortier, J., Hayes, D. J., Carriquiry, M., Dong, F., Du, X., Elobeid, A., Fabiosa, J. F., and Tokgoz, S. Sensitivity of Carbon Emission Estimates from Indirect Land-Use Change. 09-WP 493. 2009. Center for Agricultural and Rural Development, Iowa State University.
95	[275]	2009		Erickson, Brent and Biotechnology Industry Organization. Proposed Regulations to Implement the Low Carbon Fuel Standard. Comments of Biotechnology Industry Organization. 4-23-2009. California Environmental Protection Agency.
96	[295]	2009	X	European Union, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC," 5.06.2009 (2009).
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111	{Prabhu, 2009 21305 /id}	2009	X	Prabhu A, Pham C, Glabe A, and J.Duffy: Detailed California-Modified GREET Pathway for Renewable Diesel from Midwest Soybeans. Draft V.2.1 CARB(2009).

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Appendix X. Literature Sources Consulted for LCA Assessments of Biodiesel and Renewable Diesel (cont.)

Study No.	Ref. No.	Year	in Data Base	Citation
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119	[601]	2009	X	Su C-L and Lee Y.-M.: Development status and life cycle inventory analysis of biofuels in Taiwan. Energy Policy, 37(2), 754-758 (2009).
120	[602]	2009		Tipper, R., Hutchinson, C., and Brander, M. A Practical Approach for Policies to Address GHG Emissions from Indirect Land Use Change Associated with Biofuels. Ecometrica. TP-080212-A. 1-31-2009. Greenergy.
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126	[607]	2010		Elsayed, M. A., Matthews, R., and Mortimer, N. D. Carbon and Energy Balances for a Range of Biofuels Options. B/B6/00784/REP URN/ 03/836. 2010.
127	[9]	2010	X	U.S.EPA. Renewable fuel standard program (RFS2) regulatory impact analysis. EPA-420-R-10-006. 2010. U.S. EPA.
128	[608]	2010		Iriarte, Alfredo, Joan Rieradevall, and Xavier Gabarrell. "Life cycle assessment of sunflower and rapeseed as energy crops under Chilean conditions." J. Cleaner Production 18.4 (2010): 336-45.
129	[609]	2010	X	L. T. Peiro, et al., "Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO)," 35, 889 (2010)
130	[610]	2010		Lapola, D. M., et al. "Indirect land-use changes can overcome carbon savings from biofuels in Brazil." PNAS.Early Edition (2010): 1-6.
131	[611]	2010		Mandil, C and Shihab-Eldin, A. Assessment of Biofuels Potential and Limitations. 2-1-2010. International Energy Forum (IEF).
132	[296]	2010		Morais, S., A. A. Martins, and T. M. Mata. "Comparison of allocation approaches in soybean biodiesel life cycle assessment." Journal of the Energy Institute 83.1 (2010): 48-55.
133	[301]	2010	X	Omni Tech International. Life Cycle Impact of Soybean Production and Soy Industrial Products. 2010. The United Soybean Board.
134	[612]	2010		Papong, Seksan, et al. "Life cycle energy efficiency and potentials of biodiesel production

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Study No.	Ref. No.	Year	in Data Base	Citation
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141	[303]	2010		Tyner, W. E., Taheripour, F., Zhuang, Q., Birur, D., and Baldos, U. Land Use Changes and Consequent CO2 Emissions due to U.S. Corn Ethanol Production: A Comprehensive Analysis. 2010. Purdue University, Department of Agriculture Economics.
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143	[279]	2010		Zilberman, D, G. Hochman, and D. Rajagopal. "Indirect Land Use: One Consideration Too Many in Biofuel Regulation." Agriculture and Resources Economics 2010.

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Appendix XI. LCA Studies and Results for Biodiesel and Renewable Diesel Fuel

Study No.	Primary Author	Year	Feedstock	Location of Use	Fuel Name	Case Description	CI, (g CO$_2$ eq/MJ fuel) Biofuel WTW CI	LUC CI	Ref. Fuel CI	Avg Benefit	Benefit incl ILUC
1	Sheehan	1998	Soybean	USA	BD	Single point	50.9		235.9	78%	
8	Bernesson	2004	Rapeseed	Sweden	BD	Average case	49.4		217.0	77%	
9	Carraretto	2004	Soybean	Italy	BD	Average case	12.6		19.1	34%	
18	Edwards	2006	Rapeseed	EU	BD	Average Case	49.2		88.0	44%	
		2007	Sunflower	EU	BD	Average case	31.6		88.0	64%	
19	Gartner	2006	Coconut	Finland	NExBTL	Average case	62.0				
			Oils			Single point	33.2				
			Palm Oil			Single point	53.4				
			Rapeseed			Average case	43.7				
20	Hill	2006	Soybean	USA	BD	Single point	49.0		82.3	40%	
22	Lechon	2006	Blend	EU	BD	Basecase	37.6		86.2	56%	
			Palm oil			Single point	51.3		86.2	40%	
			Rapeseed			Average case	55.8		86.2	35%	
			Soybean			Single point	37.6		86.2	56%	
			Sunflower			Single point	29.6		86.2	66%	
			Yellow Grease			Average case	10.1		86.2	88%	
24	Niederl	2006	Tallow	Austria	BD	Single point	18.0		90.0	80%	
25	Ryan	2006	Oils	EU	BD	Best-estimate	46.7		85.7	46%	
29	Barber	2007	Tallow	N.Zealand	BD	Average case	49.3		82.6	40%	
36	Hansson	2007	Rapeseed	Sweden	BD	Single point	21.8		79.5	73%	
37	Kalnes	2007	Soybean	EU	Ecofining	Average	13.4		85.6	84%	
					BD	Single point	23.6		85.6	72%	
40	Kreider	2007	Soybean	USA	BD	Average	23.5		26.0	10%	
49	Zah	2007	Palm Oil	Switz.	BD	Single point	56.1		85.7	35%	
			Rapeseed			Average	66.3		85.7	23%	
			Soybean			Average	72.6		85.7	15%	
			Yellow Grease			Average	26.8		85.7	69%	
53	Campbell	2008	Rapeseed	N. Zealand	BD	Base case	50.7		82.6	39%	
55	Delucchi	2008	Soybean	USA	BD	Single point	140.8		92.0	-53%	
56	Edwards	2008	Palm Oil	EU	NExBTL	Single point	51.4		89.5	43%	
			Palm Oil		BD	Average	45.3		89.5	49%	
			Rapeseed		NExBTL	Single point	44.6		89.5	50%	
			Rapeseed		UOP	Single point	46.2		89.5	48%	
			Rapeseed		BD	average	41.6		89.5	54%	
			Soybean		BD	average	76.4		89.5	15%	

Study No.	Primary Author	Year	Feedstock	Location of Use	Fuel Name	Case Description	CI, (g CO_2 eq/MJ fuel)			Avg Benefit	Benefit incl ILUC
							Biofuel		Ref.		
							WTW CI	LUC CI	Fuel CI		
			Sunflower		NExBTL	Single point	29.2		89.5	67%	
56	Edwards	2008	Sunflower	EU	BD	average	27.2		89.5	70%	
61	Harding	2008	Rapeseed	NA	BD	average	152.2				
63	Huo	2008	Soybean	N. America	RD	Average case	16.1		95.0	83%	
					BD	Average case	18.0		95.0	81%	
64	Jin	2008	Tallow	USA	RD	average	14.5		88.0	84%	
65	Kalnes	2008	Palm Oil	EU	Ecofining	Average	37.0		84.0	56%	
					BD	Average	42.5		84.0	49%	
			Rapeseed		Ecofining	Single point	41.0		84.0	51%	
					BD	Single point	46.0		84.0	45%	
			Tallow		Ecofining	Single point	5.0		84.0	94%	
					BD	Single point	20.0		84.0	76%	
70	Nikander	2008	Palm Oil	EU	RD	Single point	34.4				
			Rapeseed			Single point	33.4				
			Tallow			Single point	15.8				
72	Prieur	2008	Rapeseed	France	BD	Single point	12.0		81.0	85%	
			Sunflower			Single point	18.0		81.0	78%	
74	Reijnders	2008	Rapeseed	EU	BD	Average case	56.2	72.6	83.6	33%	-54%
			Soybean			Average case	62.3	761.1	83.6	25%	-885%
75	Rettenmaier	2008	Jatropha	India	RD	Single point	45.7		92.5	51%	
79	Russi	2008	Rape/Sun	Italy	BD	average	25.6				
80	S&T²	2008	Canola	N. America	BD	Basecase	19.5		89.0	78%	
			Soybean			Basecase	26.0		89.0	71%	
81	Searchinger	2008	Soybean	USA	BD	Baseline	43.4	202	95.0	54%	-158%
83	UFOP	2008	Palm Oil	Germany	RD	Single point	28.7	114.3	83.8	66%	-71%
					BD	Single point	25.9	112.8	83.8	69%	-66%
			Rapeseed		RD	Single point	47.8	33.2	83.8	43%	3%
					BD	Default CI/ Max ILUC	45.2	36.2	83.8	46%	3%
			Soybean		RD	Avg CI/ Max ILUC	36.6	174.3	83.8	56%	-152%
					BD	Average case	34.4	172.1	83.8	59%	-146%
89	CARB	2009	Yellow Grease	CA, USA	BD	average	13.8		94.7	85%	
			Tallow		BD	average	29.5		94.7	69%	
96	EC-RED	2009	Palm oil	EU	RD	average typical	38.5		83.8	54%	
					BD	average typical	43.0		83.8	49%	
			Rapeseed		RD	Single point-typical	41.0		83.8	51%	
					BD	Typical	46.0		83.8	45%	
			Soybean		BD	Typical	50.0		83.8	40%	

Study No.	Primary Author	Year	Feedstock	Location of Use	Fuel Name	Case Description	CI, (g CO_2 eq/MJ fuel) Biofuel WTW CI	LUC CI	Ref. Fuel CI	Avg Benefit	Benefit incl ILUC
			Sunflower		RD	Typical	29.0		83.8	65%	
96	EC-RED	2009	Sunflower	EU	BD	Typical	35.0		83.8	58%	
			Yellow Grease		BD	Typical	10.0		83.8	88%	
100	Hu	2009	Soybean	China	BD	Single point	29.7		91.4	68%	
			Rapeseed		Ecofining	Single point	41.0		85.9	52%	
			Rapeseed		BD	Single point	52.6		85.9	39%	
102	Kalnes	2009	Soybean	EU	Ecofining	average value	33.1		85.9	62%	
			Soybean		BD	average vale	36.3		85.9	58%	
105	Lardon	2009	Algae	France	BD	Average	0.0				
			Jatropha		BD	Basecase	52.0		102.6	49%	
109	Ou	2009	Soybean	China	BD	Basecase	110.5		102.6	-8%	
			Yellow Grease		BD	Basecase	74.8		102.6	27%	
110	Panichelli	2009	Soybean	Argentina	BD	0	48.9				
113	CARB	2009	Soybean	CA, USA	RD	Basecase	20.2	62	94.7	79%	13%
					BD	Basecase	21.3	62	94.7	78%	12%
119	Su	2009	Soybean	Taiwan	BD	Single point	78.1				
		2010	Rapeseed		BD	Single point	73.4				
			Algae		BD	Average	36.8		91.9	60%	
127	EPA	2010	Soybean	USA	BD	Basecase	8.4	31.98	91.8	91%	56%
			Yellow Grease		BD	Basecase	13.0		91.8	86%	
129	Peiro	2010	Yellow Grease	Italy	BD	Basecase	8.0				
			Coconut		RD	Average-typical	43.9		86.4	49%	
			Coconut		BD	Average-typical	41.5		86.4	52%	
			Corn oil		BD	Average-typical	17.7		86.4	80%	
			Jatropha		RD	Single point-typical	27.8		86.4	68%	
			Jatropha		BD	Single point-typical	26.0		86.4	70%	
			Palm oil		RD	Average-typical	41.7		86.4	52%	
			Palm oil		BD	average	44.3		86.4	49%	
136	RTFO	2010	Rapeseed	UK	RD	typical values	41.0		86.4	53%	
			Rapeseed		BD	typical values	45.9		86.4	47%	
			Soybean		RD	typical values	49.5		86.4	43%	
			Soybean		RD	typical values	52.7		86.4	39%	
			Soybean		BD	typical values	49.8		86.4	42%	
			Sunflower		RD	typical values	31.3		86.4	64%	
			Sunflower		BD	typical values	34.6		86.4	60%	
			Tallow		BD	typical values	12.9		86.4	85%	
			Yellow Grease		BD	typical values	14.1		86.4	84%	

Appendix XIIa. LCA Studies and Results by Feedstock (not including ILUC): Soybean
(Studies not included in determination of averages are shown with grey highlighting.)

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm CO$_{2\,eq}$/ MJ $_{fuel}$)		Avg % Benefit
							Direct	Ref.Fuel CI	
Biodiesel	1	Sheehan	1998	Soybean	USA	Single	50.9	235.9	78%
	9	Carraretto	2004	Soybean	Italy	Average	12.6	19.1	34%
	20	Hill	2006	Soybean	USA	Single	49.0	82.3	40%
	22	Lechon	2006	Soybean	EU	Single	37.6	86.2	56%
	37	Kalnes	2007	Soybean	EU	Single	23.6	85.6	72%
	40	Kreider	2007	Soybean	USA	Average	23.5	26.0	10%
	49	Zah	2007	Soybean	Switzerland	Average	72.6	85.7	15%
	55	Delucchi	2008	Soybean	USA	Single	140.8	92.0	-53%
	56	Edwards	2008	Soybean	EU	Average	76.4	89.5	15%
	63	Huo	2008	Soybean	N. America	Average	18.0	95.0	81%
	74	Reijnders	2008	Soybean	EU	Average	62.3	84.3	25%
	80	S&T²	2008	Soybean	N. America	Basecase	26.0	89.0	71%
	81	Searchinger	2008	Soybean	USA	Baseline-NO ILUC	43.4	95.0	54%
	83	UFOP	2008	Soybean	Germany	Average	34.4	83.8	59%
	96	EC-RED	2009	Soybean	EU	Typical	50.0	83.8	40%
	109	Ou	2009	Soybean	China	Basecase	110.5	102.6	-8%
	110	Panichelli	2009	Soybean	Argentina	Single	48.9		
	113	CARB	2009	Soybean	CA, USA	Basecase	21.3	94.7	78%
	127	EPA	2010	Soybean	USA	Basecase	8.4	91.8	91%
	136	RTFO	2010	Soybean	UK	Typical	49.8	86.4	42%
	100	Hu	2009	Soybean	China	Single	29.7	91.4	68%
	102	Kalnes	2009	Soybean	EU	Average	36.3	85.9	58%
	119	Su	2009	Soybean	Taiwan	Single	78.1		
								Average	52%
								Standard Deviation	21%
								Count	15
Renewable Diesel	37	Kalnes	2007	Soybean	EU	Average	13.4	85.6	84%
	102	Kalnes	2009	Soybean	EU	Average	33.1	85.9	62%
	63	Huo	2008	Soybean	N. America	Average	16.1	95.0	83%
	83	UFOP	2008	Soybean	Germany	Average (max ILUC)	36.6	83.8	56%
	113	CARB	2009	Soybean	CA, USA	Basecase	20.2	94.7	79%
	136	RTFO	2010	Soybean	UK	Typical	49.5	86.4	43%
	136	RTFO	2010	Soybean	UK	Typical	52.7	86.4	39%
								Average	64%
								Standard Deviation	19%
								Count	7

Appendix XIIb. LCA Studies and Results by Feedstock (not including ILUC): Rapeseed
(Studies not included in determination of averages are shown with grey highlighting.)

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm CO$_2$ eq/ MJ fuel) Direct	Ref. Fuel	Avg. % Benefit
FEEDSTOCK: RAPESEED									
Biodiesel	8	Bernesson	2004	Rapeseed	Sweden	Average	49.4	217.0	77%
	18	Edwards	2006	Rapeseed	EU	Average	49.2	88.0	44%
	22	Lechon	2006	Rapeseed	EU	Average	55.8	86.2	35%
	36	Hansson	2007	Rapeseed	Sweden	Single	21.8	79.5	73%
	49	Zah	2007	Rapeseed	Switzerland	Average	66.3	85.7	23%
	53	Campbell	2008	Rapeseed	New Zealand	Base case	50.7	82.6	39%
	56	Edwards	2008	Rapeseed	EU	Average	41.6	89.5	54%
	61	Harding	2008	Rapeseed	NA	Average	152.2		
	65	Kalnes	2008	Rapeseed	EU	Single	46.0	84.0	45%
	72	Prieur	2008	Rapeseed	France	Single	12.0	81.0	85%
	74	Reijnders	2008	Rapeseed	EU	Average	56.2	84.3	33%
	83	UFOP	2008	Rapeseed	Germany	Default (max ILUC)	45.2	83.8	46%
	96	EC-RED	2009	Rapeseed	EU	Typical	46.0	83.8	45%
	136	RTFO	2010	Rapeseed	UK	Typical	45.9	86.4	47%
	102	Kalnes	2009	Rapeseed	EU	Single	52.6	85.9	39%
	119	Su	2010	Rapeseed	Taiwan	Single	73.4		
							Average		47%
							Standard Deviation		17%
							Count		12
Renewable Diesel	65	Kalnes	2008	Rapeseed	EU	Single	41.0	84.0	51%
	102	Kalnes	2009	Rapeseed	EU	Single	41.0	85.9	52%
	19	Gartner	2006	Rapeseed	Finland	Average	43.7		
	56	Edwards	2008	Rapeseed	EU	Single	44.6	89.5	50%
	83	UFOP	2008	Rapeseed	Germany	Single	47.8	83.8	43%
	96	EC-RED	2009	Rapeseed	EU	Typical	41.0	83.8	51%
	136	RTFO	2010	Rapeseed	UK	Typical	41.0	86.4	53%
	70	Nikander	2008	Rapeseed	EU	Single	33.4		
	56	Edwards	2008	Rapeseed	EU	Single	46.2	89.5	48%
							Average		49%
							Standard Deviation		4%
							Count		5

Appendix XIIc,d. LCA Studies and Results by Feedstock (not including ILUC):
Palm Oil, Tallow
(Studies not included in determination of averages are shown with grey highlighting.)

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm $CO_{2\,eq}$/ MJ $_{fuel}$) Direct	Ref. Fuel	Avg % Benefit
FEEDSTOCK: Palm Oil									
Biodiesel	22	Lechon	2006	Palm oil	EU	Single	51.3	86.2	40%
	49	Zah	2007	Palm Oil	Switzerland	Single	56.1	85.7	35%
	56	Edwards	2008	Palm Oil	EU	Average	45.3	89.5	49%
	65	Kalnes	2008	Palm Oil	EU	Average	42.5	84.0	49%
	83	UFOP	2008	Palm Oil	Germany	Single	25.9	83.8	69%
	96	EC-RED	2009	Palm oil	EU	Average	43.0	83.8	49%
	136	RTFO	2010	Palm oil	UK	Average	44.3	86.4	49%
							Average		49%
							Standard Deviation		12%
							Count		6
Renewable Diesel	65	Kalnes	2008	Palm Oil	EU	Average	37.0	84.0	56%
	19	Gartner	2006	Palm Oil	Finland	Single	53.4		
	56	Edwards	2008	Palm Oil	EU	Single	51.4	89.5	43%
	83	UFOP	2008	Palm Oil	Germany	Single	28.7	83.8	66%
	96	EC-RED	2009	Palm oil	EU	Average	38.5	83.8	54%
	136	RTFO	2010	Palm oil	UK	Average	41.7	86.4	52%
	70	Nikander	2008	Palm Oil	EU	Single	34.4		
							Average		55%
							Standard Deviation		9%
							Count		4

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm $CO_{2\,eq}$/ MJ $_{fuel}$) Direct	Ref.Fuel CI	Avg % Benefit
FEEDSTOCK: Tallow									
Biodiesel	29	Barber	2007	Tallow	N. Zealand	Average	49.3	82.6	40%
	89	CARB	2009	Tallow	CA, USA	Average	29.5	94.7	69%
	136	RTFO	2010	Tallow	UK	Typical	12.9	86.4	85%
	24	Niederl	2006	Tallow	Austria	Single	18.0	90.0	80%
	65	Kalnes	2008	Tallow	EU	Single	20.0	84.0	76%
							Average		70%
							Standard Deviation		18%
							Count		5
Renewable	65	Kalnes	2008	Tallow	EU	Single	5.0	84.0	94%
	64	Jin	2008	Tallow	USA	Average	14.5	88.0	84%
	70	Nikander	2008	Tallow	EU	Single	15.8		
							Average		89%
							Standard Deviation		
							Count		2

Appendix XIIe,f. LCA Studies and Results by Feedstock (not including ILUC):
Yellow Grease, Sunflower
(Studies not included in determination of averages are shown with grey highlighting.)

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm $CO_{2\ eq}$/ MJ $_{fuel}$) Direct	Ref. Fuel	Avg % Benefit
FEEDSTOCK: Yellow Grease									
Biodiesel	22	Lechon	2006	Y. Grease	EU	Average	10.1	86.2	88%
	49	Zah	2007	Y. Grease	Switzerland	Average	26.8	85.7	69%
	89	CARB	2009	Y. Grease	CA, USA	Average	13.8	94.7	85%
	96	EC-RED	2009	Y. Grease	EU	Typical	10.0	83.8	88%
	109	Ou	2009	Y. Grease	China	Basecase	74.8	102.6	27%
	127	EPA	2010	Y.Grease	USA	Basecase	13.0	91.8	86%
	129	Peiro	2010	Y. Grease	Italy	Basecase	8.0		
	136	RTFO	2010	Y.Grease	UK	Typical	14.1	86.4	84%
								Average	75%
								Standard Deviation	22%
								Count	7

	Study No.	Primary Author	Year	Feedstock	Location of Use	Case Description	Carbon Intensity (gm $CO_{2\ eq}$/ MJ $_{fuel}$) Direct	Ref.Fuel	Avg % Benefit
FEEDSTOCK: Sunflower									
Biodiesel	18	Edwards	2007	Sunflower	EU	Average	31.6	88.0	64%
	22	Lechon	2006	Sunflower	EU	Single	29.6	86.2	66%
	56	Edwards	2008	Sunflower	EU	Average	27.2	89.5	70%
	72	Prieur	2008	Sunflower	France	Single	18.0	81.0	78%
	96	EC-RED	2009	Sunflower	EU	Typical	35.0	83.8	58%
	136	RTFO	2010	Sunflower	UK	typical	34.6	86.4	60%
								Average	66%
								Standard Deviation	7%
								Count	6
Renewable Diesel	56	Edwards	2008	Sunflower	EU	Single	29.2	89.5	67%
	96	EC-RED	2009	Sunflower	EU	Typical	29.0	83.8	65%
	136	RTFO	2010	Sunflower	UK	Typical	31.3	86.4	64%
								Average	66%
								Standard Deviation	2%
								Count	3

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