Comparative Esterification of Agricultural Oils for Biodiesel Blending

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EXECUTIVE SUMMARY

Biodiesel, an alternative to traditional diesel fuel, is produced from renewable resources such as animal fats and vegetable oils. The oils and fats are most often reacted with methanol or ethanol in the presence of sodium hydroxide to form methyl or ethyl esters and glycerin. The esters are then blended with petroleum diesel in concentrations of up to 20% to produce transportation fuel. The main impediment to widespread commercial development of biodiesel technology is cost, both for raw materials, energy and waste by-product disposal. The objective of this research was to develop technical and economic data for the production of biodiesel from a variety of Arkansas based feedstocks. Biodiesel was produced from chicken fat fractions as well as various grades of refined and unrefined rice bran and soybean oils using a single, well established batch procedure from the literature. Fuel property tests were performed on the resulting biodiesels including flash point, heat of combustion, copper corrosion, density, kinematic viscosity, sulfated ash, cloud point, cetane number and lubricity. Economic feasibility was established by calculation of cross breakeven prices at various levels of input and output prices and quantities. Because this project utilized Arkansas produced oils and waste materials as feedstocks, and resulted in a fuel that can be used both by farmers and truckers as a transportation fuel, it fits well within the MBTC mission of improving the quality of U.S. rural life through transportation.

The results of this study show that biodiesel can be produced from a variety of vegetable oil/animal fat feedstocks of varying quality, producing B100 biodiesel that, in general, satisfies ASTM requirements. Although the single biodiesel production protocol that was followed for each of the feedstocks will not necessarily optimize biodiesel yield, the single protocol does represent a method for easily comparing the economics of producing biodiesel from these feedstocks.

Material balance calculations show that, as the quality of the oil/fat increases, the yield of biodiesel increases as well. At the same time, less methanol is required for reaction and less glycerin and unreacted material are produced. As an example, an average of 130 ml of biodiesel, 17.61 g of glycerin and 13 ml of unreacted material were produced from 150 ml of refined, bleached rice bran oil and 30.3 ml of methanol. By contrast, an average of 69 ml of biodiesel, 30.71 g of glycerin and 58 ml of unreacted material was produced from 150 ml of crude rice bran oil and 32.8 ml of methanol. Refined, bleached soybean oil, degummed soybean oil, refined, bleached rice bran oil and high yield chicken fat produced the most biodiesel, yielding an average of 0.88 ml of biodiesel per ml of oil/fat.

In performing a variety of ASTM tests on the biodiesel samples, all of the samples tested met the standards for cetane number (only two samples tested), heat of combustion (Mead Biofuel lower heating value standard), cloud point (with assumptions), and copper corrosion. No standard exists for lubricity, although a major feature of biodiesel is its ability to yield increased lubricity. Only some of the samples met the standards for kinematic viscosity, flash point and sulfated ash. It is believed that perhaps a better job of preparing the biodiesels would have led to the samples also meeting these standards, but this has not been substantiated.

Given the effects of feedstock quality discussed above, the economic evaluation revealed that the choice of least-cost feedstock for biodiesel production has two main determinants. These are the price of the feedstock and the biodiesel yield that may be affected by the level of refinement of a particular feedstock. By comparison, methanol efficiency (the ratio of required methanol to biodiesel produced) affects biodiesel cost only marginally. It is expected that processing charges (overhead, capital costs, energy, labor and transportation – estimated at approximately $0.15 per gallon of biodiesel) will be affected mostly by plant location and to a much lesser extent by feedstock selection.

Given the importance of feedstock raw material price, a four and a half year history of weekly commodity input prices was collected and used to calculate average biodiesel cost (the cost of fat/oil input, methanol and sodium hydroxide required) for each feedstock category and level of refinement within each feedstock category. Since the same standard batch procedure was used for all feedstocks, processing charges are similar across feedstock and only biodiesel cost differences across feedstock (a result of varying biodiesel yield, methanol use and byproduct output) were analyzed.

If no byproduct value or cost is assumed, high-yielding chicken fat is the least cost feedstock with an average biodiesel cost of $1.17/gal (excluding non-feedstock processing costs). However, there are concerns that biodiesel derived from chicken fat may exceed the ASTM limits of allowable sulfated ash. Further investigation is required to determine whether this issue can be resolved by further processing or whether this issue remains with the use of chicken fat.

Meeting ASTM sulfated ash quality standards resulted in a least-cost biodiesel blend (post production) involving degummed soybean oil (58%) and chicken fat (42%). The price of this biodiesel blend was approximately $1.50/gal with no byproduct value. If a disposal fee on byproducts is imposed, this increases the cost by $0.03/gal. If the glycerin byproduct is sold, the cost of biodiesel can drop considerably (as low as $0.18/gal using a sale price of $0.77/lb for glycerin and no disposal cost for the unreacted material). Since i) glycerin quality was not assessed and is expected to be relatively low, and ii) glycerin production from biodiesel is expected to put supply pressure on glycerin prices, it may be more realistic to assume a biodiesel cost (including glycerin sales) somewhere between $0.85 and $1.50/gal using average, historical prices for feedstock inputs.

Prices for feedstocks change over time, however, and an analysis of input price risk management strategies pointed to an advantage for using soybean oil, as price risk may be hedged using futures and options. At the same time, chicken fat is an attractive feedstock from the perspective of both low cost and low input price risk. Further, since fats and oils tend to respond to demand and supply fluctuations in a similar fashion (price series are cointegrated), little price risk diversification possibilities exists to manage input price risk by diversify operations by using several feedstocks at a particular biodiesel facility.

Finally, since byproduct value implications can be very large especially for larger operations, further refinement in production processing methodology to enhance byproduct value and additional testing on the type of variation in material balances that may be apparent with different feedstocks is required to provide more explicit recommendations about plant location on the basis of least-cost inputs.

ACKNOWLEDGEMENTS

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INTRODUCTION

Biodiesel, an alternative to traditional diesel fuel, is produced from renewable resources such as animal fats and vegetable oils. Biodiesel may be produced in several ways (Sinha and Misra, 1997), but the most common technique is esterification. In this process, glycerides in the fats and oils are reacted with an alcohol in the presence of a catalyst to produce esters and glycerin. Specifically, the oils and fats are most often reacted with methanol or ethanol in the presence of sodium hydroxide to form methyl or ethyl esters and glycerin. In the sense that different feedstocks have diverse fats and oils (Goering et al., 1982), this process can require various amounts of alcohols and catalyst to generate esters as well as byproducts (e.g. glycerin) with a range of quality attributes. The esters are then blended with petroleum diesel in concentrations of up to 20% to produce transportation fuel. Biodiesel as a fuel has significant advantages over diesel alone as esters reduce sulfur emissions (an EPA concern), enhance lubricity and have engine cleaning properties (Ma and Hanna, 1999). Because biodiesel use reduces our dependence on imported petroleum, legislation has been introduced in the U.S. Congress that will provide a partial exemption of the diesel fuel excise tax to fuel suppliers that choose to include low-blend biodiesel. In addition, fats and oils used for biodiesel production spur demand for these agricultural products and thereby enhance profitability in the U.S. agricultural sector.

The main impediment to widespread commercial development of biodiesel technology is cost, both for raw materials, energy and waste by-product disposal. Biodiesel is most often produced from soybean oil, requiring 7.7 pounds of oil to produce one gallon of biodiesel (Tyson, 2002). As is noted in Table 1, other oil and fat containing raw materials may also serve as feedstocks including rice bran, corn, cottonseed and chicken fat, all of which are produced in Arkansas (Ash and Dohlman, 2003; USDA, 1999 & 2002). These alternative fats and oils differ primarily in cost (see Figure 1) but also in terms of their current use. Rice bran, for example, is currently used as a low cost additive to feed rations. In addition, Riceland, an Arkansas producer cooperative, is currently the only plant producing rice bran oil from rice bran in the U.S. Should rice bran oil prove to be a feasible feedstock for ester production it is conceivable that more rice bran would move to this end use. Similar trends are apparent in chicken fat produced in large quantities in the U.S. Of interest is the degree of substitutability, relative price levels and degree of refinement at which these fats and oils become desirable alternatives to soybean oil in the production of esters for biodiesel use.

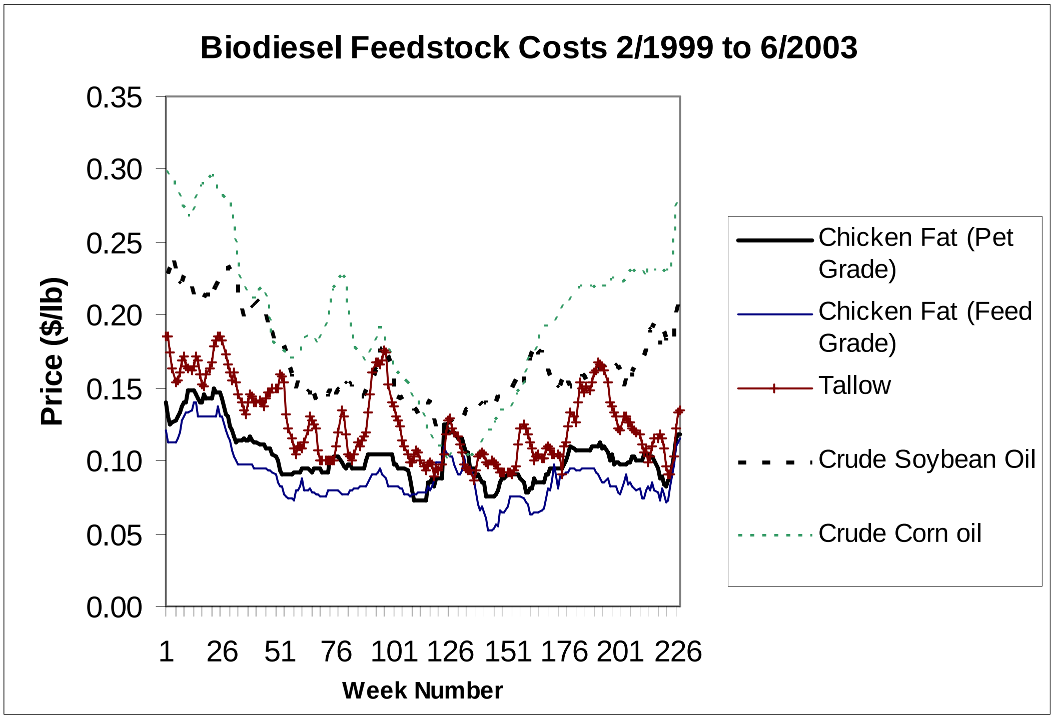
The choice of the least-cost feedstock for biodiesel production is sensitive to changes in process operating costs. These operating costs include the price of the fat/oil feedstock, chemical catalysts (sodium hydroxide, methanol), energy, labor, etc. Since different feedstocks only require changing levels of methanol when using a standard batch procedure, the least-cost feedstock may be determined by the cost of the feedstock as well as changing levels of byproduct output and methanol use. For example, chicken fat may be the least expensive feedstock (possibly $0.05 - 0.15/lb for chicken fat versus $0.09 - 0.19/lb for tallow or $0.12 - $0.24/lb for vegetable oil) but its use may require additional methanol or give a lower biodiesel yield when compared to other oils and fats. Therefore, the choice of overall least-cost feedstock hinges on all of these factors, their inherent variation in product characteristics and costs over time, and their contribution to total operating expense.

The objective of this research was to develop technical and economic data for the production of biodiesel from a variety of Arkansas based feedstocks. Biodiesel was produced from chicken fat fractions as well as various grades of refined and unrefined rice bran and soybean oils using a single, well established batch procedure from the literature. Fuel property tests were performed on the resulting biodiesels including flash point, heat of combustion, copper corrosion, density, kinematic viscosity, sulfated ash, cloud point, cetane number and lubricity. Economic feasibility was established by calculation of cross breakeven prices at various levels of input and output prices and quantities. Because this project utilized Arkansas produced oils and waste materials as feedstocks and resulted in a fuel that can be used both by farmers and truckers as a transportation fuel, it fits well within the MBTC mission of improving the quality of U.S. rural life through transportation.

Table 1. U.S. Use of Specific Fats and Oils Produced[1]

Feedstock	**U.S. Disappearance** 2002 (mil lb)	**% of Total Edible Fats & Oils**
Tallow	1,500	6.4%
Poultry Fat	1,400	6.0%
Soybean Oil	17,350	74.3%
Lard	982	4.2%
Corn Oil	1,400	6.0%
Cottonseed Oil	725	3.1%
Total	**23,357**	

[1] Edible tallow and lard are only a fraction of animal fats produced. Chicken fat makes up approx. 5% of an eviscerated chicken. At a carcass weight of 3.5 lbs and 8 billion birds slaughtered in the U.S. this amounts to 1.4 billion pounds of chicken fat, of which some fraction would be usable for biodiesel production. A large degree of quality attributes are present for animal fats and oils. These numbers therefore need to be viewed with caution.



Notes: Prices for soybean oil are crude prices. Added processing incurs a charge of $0.01/lb. Chicken fat, and tallow prices can vary considerably given different quality grades. Most of these prices series react to changes in the fats & oils markets in the same fashion over time (i.e. if soybean oil supply is low and prices increase a similar price increase is likely to occur for the other fats & oils and vice versa).

Figure 1. Weekly Vegetable Oil and Animal Fat Prices

METHODS

Oil/Fat Feedstocks

As is noted in Table 2, seven vegetable oils and two animal fat feedstocks were obtained for use in this project. Four grades of soybean oil (crude, degummed, refined, and refined and bleached oil) were obtained from Riceland Foods. As the level of refinement increased from crude oil to refined and bleached oil, the amount of particulates and degree of cloudiness of the oil decreased, while the color lightened and clarity increased. Refined, bleached soybean oil is a clean, clear, light yellow oil that is similar in color to grocery store grade vegetable oil. Similarly, three grades of rice bran oil (crude, refined, and refined and bleached oil) were obtained, also from Riceland Foods. Again, as the level of refinement increased from crude oil to refined and bleached oil, the amount of particulates and degree of cloudiness of the oil decreased, while the color lightened and clarity increased. Refined, bleached rice bran oil is a clean, clear, yellow oil that is slightly darker than refined, bleached, soybean oil. Two grades of chicken fat fractions (pet grade and feed grade) were obtained from Tyson Foods. Both of the chicken fat samples were dark, brownish-yellow, sludgy liquid that became solid at cool temperatures. The feed grade chicken fat sample contained solid particles.

Table 2. Vegetable Oil/Animal Fat Feedstocks for Biodiesel Production

Feedstock	Source	Brief Description
Refined, bleached soybean oil	Riceland Foods	A clean, clear, light yellow oil similar in color to grocery store grade vegetable oil.
Refined soybean oil	Riceland Foods	A clean, clear oil that is orange in color.
Degummed soybean oil	Riceland Foods	A clear oil that is a slightly darker orange than refined soybean oil, and has small amounts of cloudiness or gel floating in the oil.
Crude soybean oil	Riceland Foods	The least refined of the above with cloudiness and other particles in suspension.
Refined, bleached rice bran oil	Riceland Foods	A clean, clear, yellow oil that is slightly darker than refined, bleached, soybean oil.
Refined rice bran oil	Riceland Foods	A clean, clear, dark yellow oil.
Crude rice bran oil	Riceland Foods	A dark brown, opaque oil with a light colored sediment that settles if the oil is left undisturbed for several days
Chicken fat fractions (Pet Grade)	Tyson Foods Inc.	A dark, brownish-yellow, sludgy liquid that becomes solid at cool temperatures.
Chicken fat fractions (Feed Grade)	Tyson Foods Inc.	A dark, brownish-yellow, sludgy liquid that becomes solid at cool temperatures and contains particles.

Esterification Procedure

Boocock et. al (1996) detailed a procedure for the esterification of oils to methyl esters in which a 6:1 molar ratio of methanol to oil (1:6.25 volumetric ratio) is combined with 1% NaOH (by weight of oil). The mixture was to be agitated and kept at a constant temperature of 60°C for one hour. This procedure was modified in the present work by increasing the volumetric ratio of methanol to oil to 1:2 and agitating at 55-60°C for 1.5 hours, while maintaining the same percentage of NaOH. The amount of methanol in the reaction was increased because it was found that alcohol was being lost to evaporation during the heating process. A larger volume of methanol thus ensured that excess alcohol was present during esterification. This excess methanol can be easily recovered during distillation in the laboratory. Of course, significant excesses should be avoided at the commercial level. The reaction time was increased to permit increased conversion of triglycerides, and to hopefully improve the quality of biodiesel prepared from lower grade raw materials. The weight percentage of NaOH was not varied from the original work of Boocock et al., but could be increased for some of the lower grade oils to help neutralize the higher levels of acidity.

This standard procedure was used in the preparation of methyl esters from all of the feedstocks, regardless of the type of fat or oil used as the feedstock or the degree of refinement. It is realized that modifications of the standard procedure will be required to maximize the yields of methyl esters from each feedstock, but this will be the subject of later work. The use of a single procedure for esterification simplifies economic projections, a major focus of the present work, while attempting to quickly address process feasibility.

ASTM Testing of Biodiesel

Meadbiofuel (www.meadbiofuel.com) has compiled a listing of the fuel properties of biodiesel, as well the material compatibility of biodiesel in the presence of a variety of construction materials (see Tables 3 and 4). The National Biodiesel Board (www.biodiesel.org) compiled a list of the biodiesel properties, the ASTM methods used in testing the properties, and the allowable limits for each of the properties (see Table 5). A number of these important properties were evaluated for the biodiesel produced from the soybean oils, rice bran oils and chicken fat fractions used in this research.

Table 3. Fuel Properties of Biodiesel (www.meadbiofuel.com)

Fuel Property	**Composition**
Fuel Standard	ASTM 6751-02
Fuel Composition	C_{12}-C_{22} FAME
Lower Heating Value, BTU/gal	117,093
Kinematic Viscosity, 40°C, cS	1.9-6.0
Specific Gravity, 60°F/60°F	0.88
Density, 15°C, lb_m/gal	7.0328
Water, wt % max	0.05
Carbon, wt %	77
Hydrogen, wt %	12
Oxygen, by dif., %	11
Sulfur, wt %	0.0-0.0024
Boiling point, °C	182-338
Flash point, °C	100-170
Cloud point, °C	-3 to 12
Pour point, °C	-15 to 10
Cetane Number	48-65
Stoichiometric Air/Fuel Ratio	13.8
BOCLE scuff, grams wt	>7,000
HFRR, μm	314

Table 4. Biodiesel Material Compatibility (www.meadbiofuel.com)

Material	BXX	Effect Compared to Diesel Fuel
Teflon	B100	Little change
Nylon 66	B100	Little change
Nitrile	B100	Hardness reduced 20%
Vitron A401-C	B100	Swell increased 18%
Vitron GFLT	B100	Little change
Fluorosilicon	B100	Little change
Fluorosilicon	B100	Swell increased 7%
Polyurethane	B100	Little change in hardness
Polyurethane	B100	Swell increased 6%
Polypropylene	B100	Hardness reduced 10%
Polypropylene	B100	Swell increased 8-15%
Polyvinyl	B100	Much worse
Polyvinyl	B50	Worse
Polyvinyl	B40	Worse
Polyvinyl	B30	Worse
Polyvinyl	B20	Comparable
Polyvinyl	B10	Comparable
Tygon	B100	Worse

Table 5. Specifications for Biodiesel (B100) (www.biodiesel.org)

Property	ASTM Method	Limits	Units
Flash point	D93	130, min	°C
Water and sediment	D2709	0.050, max	% vol
Kinematic viscosity, 40°C	D445	1.9-6.0	mm^2/sec, cS
Sulfated ash	D874	0.020, max	% mass
Sulfur	D5453	0.05, max	% mass
Copper strip corrosion	D130	No. 3, max	
Cetane number	D613	47, min	
Cloud point	D2500	report	°C
Carbon residue, 100% sample	D4530	0.050, max	% mass
Acid number	D664	0.80, max	mg KOH/gm
Free glycerin	D6584	0.020, max	% mass
Total glycerin	D6584	0.240, max	% mass
Phosphorus content	D4951	0.001, max	% mass
Distillation temp, atmospheric equivalent temp, 90% recovered	D1160	360, max	°C

A listing of ASTM tests used in evaluating each of the produced methyl esters is shown in Table 6, including the ASTM reference and where the test was performed. A limited number of representative tests were performed due to budget, equipment and time limitations. Samples for various runs were mixed before performing the quality testing to ensure a more representative average measurement of quality characteristics. The objective of this task was to evaluate whether each of the biodiesel fuels meets current National Biodiesel Board ASTM D6751-02 standards. This table is followed by a statement of the importance of the test in biodiesel utilization and a brief description of each of the tests.

Table 6. ASTM Tests used in Biodiesel Evaluations

Test	ASTM Reference	Equipment Requirements	Performed by
Cetane number	D6890-03	Standardized diesel engine	AET*
Lubricity	D6078-99	Standardized diesel engine	AET*
Kinematic viscosity	D445-94	Viscometer	U of A
Flash point	D3828-93	ERDCO Rapid Tester	U of A
Heat of combustion	D240-92	Bomb calorimeter	U of A
Cloud point	D2500-91	Test jar, cooling jacket	U of A
Sulfated ash	D874-95	High temperature oven, sulfuric acid	U of A
Copper corrosion	D130-94	Water bath, copper strips, test tubes	U of A

*AET represents Advanced Engine Technology, Limited (AET) of Ontario, Canada.

Cetane Number. The cetane number is a measure of the ignition performance of a diesel fuel and is obtained by comparing it to reference fuels in a standard single cylinder, four-stroke cycle, variable compression ratio, indirect injected diesel engine. The higher the cetane number, the better the burning characteristics. The cetane number was measured for selected samples by Advanced Engine Technology, Limited (AET) of Ontario, Canada.

Lubricity. Lubricity measures the lubricating property, or load carrying ability of a fluid. A low lubricity may cause high wear and scarring of the engine, while a high lubricity fuel may result in reduced engine wear and a longer component life. Lubricity was measured as the average wear scar diameter in μm for selected samples by Advanced Engine Technology, Limited (AET) of Ontario, Canada.

Kinematic Viscosity. Kinematic viscosity is the resistance to flow of a fluid under gravity, and is measured using a calibrated glass capillary viscometer. A Canon-Fenske Routine Viscometer was used for these measurements, but the bath as described by ASTM was not used. Suction was applied to cause the sample to rise above the first marking line. The sample was then allowed to flow down past the second marking line. The efflux time was calculated as the time required to pass between the two marking lines, and the kinematic viscosity was calculated as the product of the efflux time and the viscometer constant.

Flash Point. The flash point of a liquid is the minimum temperature at which sufficient vapor evolves from the surface of the liquid to generate a flame when the vapor contacts an ignition source. The test is performed by incrementally raising the temperature of the fuel and exposing it to a flame until the flash point is reached (the minimum temperature at which a flame appears and instantaneously propagates itself over the surface of the specimen. Using an ERDCO Rapid Tester, 4 ml of sample fuel was injected into the tester. The test pilot flame was lit, and a hatch was opened to expose the flame to the fuel at the desired temperature.

Heat of Combustion. The heat of combustion measures the quantity of energy released when a sample of fuel is burned in a constant volume enclosure. An Oxygen Bomb Calorimeter was used to perform this test. A sample of test fuel and pure oxygen were charged to the bomb calorimeter. The initial weight of the sample and ambient temperature were recorded. The sample was ignited. The final temperature and weight of the sample were recorded to calculate the heat of combustion.

Cloud Point of Petroleum Products. The cloud point is the temperature at which cloudiness, or haziness, can first be observed in a fuel, and is measured observing the fuel while the temperature is slowly decreased. The fuel sample was poured into a metal, watertight, cylindrical, flat bottom flask. Note that a flat-bottomed glass beaker was not used as described by the ASTM. The flask was placed in an ice-bath, and the temperature was recorded as the flask began to cloud up. The cloud point is found when the sample fuel turns hazy and a whitish film forms around the surface of the flask.

Sulfated Ash from Lubricating Oils and Additives. This test determines the amount of sulfated ash in a fuel or lubricating oil by heating a sample to 775°C, treating it with sulfuric acid, and heating again. The heating of sulfuric acid to 775°C can create potentially hazardous fumes, so the test was performed in a hood. The sample was placed in a crucible, and the initial weight was recorded. Using an electric-muffle furnace, the sample was heated to its combustion point, and was exposed to a test flame to completely burn the sample. After the sample had been completely burned, the residue was treated with concentrated sulfuric acid. The sample was heated again in the furnace at 700°C to a final, constant weight. The weight of the sulfated ash was recorded.

Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test. This test determines the corrosiveness of fuel to copper by submerging a copper strip in a heated sample of fuel for a specified time period. At the end of the time period, the strip is compared to the *ASTM Copper Strip Corrosion Standards* to determine the level of the fuel's corrosiveness. The copper strips were first sanded with silicon carbide paper. Using the copper strip corrosion test bomb, the copper strips were immersed in the sample. The final colors of the strips were compared with the *ASTM Copper Strip Corrosion Standards*, shown in Table 7.

Table 7. Copper Strip Classifications (from ASTM D130-94)

Classification	Designation	Description
Freshly polished strip		
1	Slight tarnish	a. Light orange, almost the same as freshly polished strip
		b. Dark orange
2	Moderate tarnish	a. Claret red
		b. Lavender
		c. Multicolored with lavender blue or silver, or both, overlaid on claret red
		d. Silvery
		e. Brassy or gold
3	Dark tarnish	a. Magenta overcast on brassy strip
		b. Multicoloered with red and green showing (peacock), but no gray
4	Corrosion	a. Transparent black, dark gray or brown with peacock green barely showing
		b. Graphite or lusterless black
		c. Glossy or jet black

RESULTS AND DISCUSSION

Material Balance Calculations

Material balances were obtained for biodiesel production from the oil and fat raw materials. The theoretical material balance is given in the literature (Freedman et al., 1986):

$$\text{Triglyceride} + 3\ \text{ROH} + \text{catalyst} \rightarrow 3\ \text{R'CO}_2\text{R} + \text{Glycerin}$$

As is noted, in addition to the methyl esters (shown as $R'CO_2R$), glycerin (or glycerol) is produced as a by-product. In experiments involving raw materials containing by-products other than triglycerides, a certain amount of sludge (soaps, unreacted triglycerides and other by-products) is also produced. In a commercial operation, the sludge will most likely require disposal or be sent to a rendering facility. Thus, material balances were prepared showing the fat/oil input, the sodium hydroxide required, the methanol used, the biodiesel produced, the glycerin by-product produced and the left over sludge that occurs. Once again, a different set of procedures may yield a higher amount of biodiesel from a given feedstock, but this was not a part of this feasibility study.

Two sets of material balances were prepared using multiple replicates because of the potential variability in the raw material:

- An initial set of materials balances where methanol was not adequately recovered from the glycerin; and,
- A second set of material balances where efforts were made to recover all of the methanol, both from the biodiesel and the glycerin.

Thus, the second set of material balances yields better material balance closure (and a more realistic picture of chemical use), while the first set of balances is useful for biodiesel yield only.

Detailed material balances are shown in the Appendix as Tables A1 and A2, and summaries of the material balance calculations are shown in Tables 8 and 9. A 90 percent material balance closure was obtained. It is generally seen that, as the quality of the oil/fat increases, the yield of biodiesel increases as well. At the same time, less methanol is required for reaction and less glycerin and unreacted material are produced. As an example, an average of 130 ml of biodiesel, 17.61 g of glycerin and 13 ml of unreacted material was produced from 150 ml of refined, bleached rice bran oil and 30.3 ml of methanol. By contrast, an average of 69 ml of biodiesel, 30.71 g of glycerin and 58 ml of unreacted material was produced from 150 ml of crude rice bran oil and 32.8 ml of methanol. Refined, bleached soybean oil, degummed soybean oil, refined, bleached rice bran oil and high yield chicken fat produced the most biodiesel, yielding an average of 0.88 ml of biodiesel per ml of oil/fat.

Table 8. Summary of Material Balance Calculations*

Oil/ Fat	ml Oil Treated	g NaOH Used	ml Methanol Used	g Glycerin Produced	ml Biodiesel Produced	ml Unreacted Material
RBSO	150	0.75	33.0-38.0	16.63-17.30	122-142	6-20
RSO	150	1	31.0-32.5	16.17-17.23	127-131	7-12
DSO	150	1	37.5	19.07-24.36	130-134	10-13
CSO	150	1	36.0-42.5	22.73-49.09	102-126	3-8
RBRBO	150	0.75	27.0-34.0	16.04-19.06	122-137	5-20
RRBO	150	1-1.25	27.0-38.0	23.03-27.04	101-128	6-31
CRBO	150	1	30.5-35.0	28.26-33.16	52-86	48-68
HYCF	150	1	35.5-43.0	15.67-24.92	108-130	5-20
LYCF	150	1	30.5-44.5	25.00-30.62	49-94	24-66

*Data ranges shown
RBSO—Refined, bleached soybean oil (2 samples)
RSO—Refined soybean oil (2 samples)
DSO—Degummed soybean oil (2 samples)
CSO—Crude soybean oil (4 samples)
RBRBO—Refined, bleached rice bran oil (4 samples)
RRBO—Refined rice bran oil (3 samples)
CRBO—Crude rice bran oil (2 samples)
HYCF—High yield chicken fat (6 samples)
LYCF—Low yield chicken fat (5 samples)

Table 9. Summary of Average Material Balance Calculations*

Oil/ Fat	ml Oil Treated	g NaOH Used	ml Methanol Used	g Glycerin Produced	ml Biodiesel Produced	ml Unreacted Material
RBSO	150	0.75	35.5	16.97	132	13
RSO	150	1	31.8	16.70	129	10
DSO	150	1	37.5	21.72	132	12
CSO	150	1	38.9	36.85	116	6
RBRBO	150	0.75	30.3	17.61	130	13
RRBO	150	1.17	31.5	24.48	111	22
CRBO	150	1	32.8	30.71	69	58
HYCF	150	1	38.9	20.86	125	11
LYCF	150	1	32.7	27.81	68	49

*Data averages shown
RBSO—Refined, bleached soybean oil (2 samples)
RSO—Refined soybean oil (2 samples)
DSO—Degummed soybean oil (2 samples)
CSO—Crude soybean oil (4 samples)
RBRBO—Refined, bleached rice bran oil (4 samples)
RRBO—Refined rice bran oil (3 samples)
CRBO—Crude rice bran oil (2 samples)
HYCF—High yield chicken fat (6 samples)
LYCF—Low yield chicken fat (5 samples)

ASTM Tests

Results from the ASTM tests on the biodiesel preparations are shown in Tables 10-18, along with the ASTM standard for B100 biodiesel when appropriate. Detailed experimental results from the tests are shown in Tables A3-A24 in the Appendix.

Cetane Number. Results from the cetane number tests are shown in Table 10. As is noted, both of the samples sent to AET for testing gave suitable cetane numbers in comparison to the ASTM standard. Additional samples were not tested due to the cost of performing these analyses.

Table 10. IQT^{TM} Test Results of Cetane Number

Biodiesel Sample	Average IQT DCN
Refined, bleached soybean oil	55.6*
High yield chicken fat	59.5*
ASTM standard	≥ 47

*Performed by AET using the ASTM D6890-03 test method

Lubricity. Results from lubricity tests, shown as the average wear scar diameter in µm, are shown in Table 11. While there is no ASTM standard for lubricity, it is known that biodiesel has a higher lubricity than diesel fuel, which helps to protect the engine from wear. Both refined, bleached soybean oil and high yield chicken fat have similar lubricities. This is an important characteristic as recent legislation to restrict sulfur content in petroleum diesel (EPA, 2004) will require an additive to increase lubricity. It has further been shown by studies conducted at NREL (Kinast, 2003) that biodiesel can sufficiently enhance low-sulfur diesel lubricity at very low concentrations (adding 0.5% of B100). This could dramatically increase the current demand for biodiesel if this lubricity enhancing additive is cost-effective and/or most socially-desirable from an environmentally sustainable point of view.

Table 11. BOTD Lubricity Test Results*

Biodiesel Sample	Avg. Wear Scar Diameter (µm)
Refined, bleached soybean oil	371.7
High yield chicken fat	370.2

*Performed by AET

Kinematic Viscosity. Results from the viscosity tests are shown in Table 12. The kinematic viscosity (cS), the density (g/cm^3) and the absolute viscosity (cP) were found for each sample. As is noted, the viscosities of all of the samples were quite similar and on the high end of the ASTM standard, perhaps indicating the presence of glycerin or free fatty acids in the biodiesel products due to poor separation in the laboratory. There was no apparent pattern in viscosity and feedstock source. Future efforts should thus concentrate on improving the separation of the biodiesel from by-products and unreacted fats and oils.

Table 12. Viscosity Results

Biodiesel Sample	Kinematic viscosity (cS)	Density (g/cm^3)	Absolute viscosity (cP)
Refined, bleached soybean oil	6.41	0.888	5.69
Refined soybean oil	6.58	0.885	5.82
Degummed soybean oil	6.76	0.892	6.03
Crude soybean oil	5.81	0.872	5.07
Refined, bleached rice bran oil	7.13	0.874	6.23
Refined rice bran oil	7.51	0.878	6.59
Crude rice bran oil	8.45	0.887	7.49
High yield chicken fat	6.40	0.858	5.49
ASTM standard	1.0-6.0		

Flash point. The results from the flash point tests are shown in Table 13. Only two of the samples (the biodiesel produced from refined, bleached soybean oil and the biodiesel produced from refined soybean oil) met the ASTM standard. Again, the presence of unconverted fats and oils or glycerin may have compromised the purity of the samples and thus altered the flash points. It seems clear that the higher quality feedstocks gave better flash points.

Table 13. Flash Point Results

Biodiesel Sample	Flash Point (°C)
Refined, bleached soybean oil	137.8
Refined soybean oil	135.0
Degummed soybean oil	118.3
Crude soybean oil	82.2
Refined, bleached rice bran oil	118.3
Refined rice bran oil	129.4
Crude rice bran oil	118.3
High yield chicken fat	76.7
ASTM standard	≥130

Heats of Combustion. Heat of combustion data for the biodiesels are presented in Table 14. While there is no ASTM heat of combustion standard, Mead Biofuel presents a lower heating value of 117,093 BTU/gal, which translates to approximately 15,950 BTU/lb. All of the heats of combustion in Table 14 are quite close, and all exceed 15,950 BTU/lb. Thus, the biodiesel samples are judged to have adequate heats of combustion.

Table 14. Heats of Combustion

Biodiesel Sample	Gross Heat of Combustion (cal/g)		Gross Heat of Combustion (BTU/lb)	
	Range	Average	Range	Average
RBSO	9,455-9,517	9,495	17,018-17,129	17,089
RSO	9,436-9,450	9,443	16,984-17,008	16,996
DSO	9,411-9,461	9,436	16,938-17,027	16,983
CSO	8,349-9,582	8,965	15,026-17,245	16,135
RBRBO	9,375-9,477	9,441	16,872-17,057	16,991
RRBO	9,528-9,630	8,572	17,148-17,332	17,228
CRBO	9,403-9,507	9,466	16,923-17,110	17,037
HYCF	9,422-9,497	9,456	16,958-17,092	17,018
Mead Biofuel		8,853		15,950

RBSO—Refined, bleached soybean oil (3 samples)
RSO—Refined soybean oil (2 samples)
DSO—Degummed soybean oil (4 samples)
CSO—Crude soybean oil (2 samples)
RBRBO—Refined, bleached rice bran oil (3 samples)
RRBO—Refined rice bran oil (3 samples)
CRBO—Crude rice bran oil (3 samples)
HYCF—High yield chicken fat (3 samples)
Mead Biofuel—www.meadbiofuel.com—lower heating value

Cloud Point. Results from cloud point tests are shown in Table 15. Due to limitations with the equipment, the temperature could not be lowered to <-2.0°C. As is noted in the table, all of the samples met the ASTM standard of -3 to 12°C (assuming that the cloud points of degummed soybean oil, crude soybean oil and crude rice bran oil were no lower than -3°C). The chicken fat biodiesel sample yielded the highest cloud point of 5.0°C.

Table 15. Cloud Point Results

Biodiesel Sample	Cloud Point (°C)
Refined, bleached soybean oil	-1.0
Refined soybean oil	0.0
Degummed soybean oil	<-2.0*
Crude soybean oil	<-2.0*
Refined, bleached rice bran oil	0.0
Refined rice bran oil	2.0
Crude rice bran oil	<-2.0*
High yield chicken fat	5.0
ASTM standard	-3 to 12

* Could not lower temperature below -2°C

Sulfated Ash. Results from the sulfated ash tests are shown in Table 16. As is noted, only half of the biodiesel samples met the ASTM standard of <0.020 percent by mass. The percentage sulfated ash was higher for the less refined feedstocks (crude soybean oil, crude rice bran oil and high yield chicken fat), and was highest for the crude rice bran oil.

Table 16. Results from Sulfated Ash Tests

Biodiesel Sample	Sulfated Ash, wt %
Refined, bleached soybean oil	0.0096
Refined soybean oil	0.0014
Degummed soybean oil	0.0011
Crude soybean oil	0.0709
Refined, bleached rice bran oil	0.0144
Refined rice bran oil	0.0464
Crude rice bran oil	0.1212
High yield chicken fat	0.0462
ASTM standard	<0.020

Copper Corrosion. Results from the copper corrosion tests are shown in Table 17. All of the samples met the ASTM standard. In fact, all of the samples showed only a slight tarnish on the copper strips, appearing almost the same as the freshly polished strip.

Table 17. Results from Copper Corrosion Tests*

Biodiesel Sample	Corrosion Category
Refined, bleached soybean oil	1a
Refined soybean oil	1a
Degummed soybean oil	1a
Crude soybean oil	1a
Refined, bleached rice bran oil	1a
Refined rice bran oil	1a
Crude rice bran oil	1a
High yield chicken fat	1a
ASTM standard	3, max

* see Table 7 for classification of corrosion categories.

ASTM Testing Summary. Table 18 presents a summary of the ASTM testing. As is noted, all of the biodiesel samples tested met the standards for cetane number (only two samples tested), heat of combustion (Mead Biofuel lower heating value standard), cloud point (with assumptions), and copper corrosion. No standard exists for lubricity, although a major feature of biodiesel is its ability to yield increased lubricity. Only some of the samples met the standards for kinematic viscosity, flash point and sulfated ash. It is believed that perhaps a better job of preparing the biodiesels would have led to the samples also meeting these standards, but this has not been substantiated.

Table 18. Biodiesel Test Summary

Does the sample meet the ASTM standard?

Biodiesel Sample	1	2	3	4	5	6	7	8
Refined, bleached soybean oil	Y	n/a	N	Y	Y*	Y	Y	Y
Refined soybean oil			N	Y	Y*	Y	Y	Y
Degummed soybean oil			N	N	Y*	Y	Y	Y
Crude soybean oil			Y	N	Y*	Y	N	Y
Refined, bleached rice bran oil			N	N	Y*	Y	Y	Y
Refined rice bran oil			N	N	Y*	Y	N	Y
Crude rice bran oil			N	N	Y*	Y	N	Y
High yield chicken fat	Y	n/a	N	N	Y*	Y	N	Y

1—Cetane number
2—Lubricity
3—Kinematic viscosity
4—Flash point
5—Heat of combustion
6—Cloud point
7—Sulfated ash
8—Copper corrosion

Y—yes, meets standard
Y*—meets Mead Biofuel lower heating value
N—no, does not meet standard
n/a—no standard exists

One of the problems encountered in producing biodiesel is the formation of a haze or cloudiness in the biodiesel when it cools to room temperature (~20-23°C). Generally, less cloudiness is observed in biodiesel produced from the more refined raw materials (i.e. refined, bleached soybean oil). The solution used to overcome the cloudiness problem was to allow the haze to form, and then centrifuge the biodiesel for ~10 minutes.

The haze settled to the bottom and the biodiesel could then be decanted into a storage jar. After centrifuging once, the biodiesel did not cloud up again.

Crude rice bran oil was used to prepare biodiesel using both base catalyzed and acid catalyzed reactions to determine which was the most effective. The base catalyzed reaction resulted in a two-phase liquid product that solidified when cooled to room temperature. The acid catalyzed reaction also produced a two phase product, but remained as a liquid at room temperature. The least dense liquid layer was almost black in color and may indicate a lower quality product. This may have been caused by a high percentage of free fatty acids in the crude rice bran. Chicken fat was also processed using both base catalyzed and acid catalyzed reactions with mixed results from each. The base catalyzed reaction resulted in the formation of a two phase product with varying degrees of solid and gel formation when cooled to room temperature. Excess base (sodium hydroxide) resulted in the formation of clumpy soaps during the reaction process. The acid catalyzed reaction also resulted in a two phase liquid product, with the desirable top phase representing only a small percentage of the total product. A two step process incorporating both acid and base catalysts may be necessary to economically produce biodiesel from chicken fat, and should be investigated further.

ECONOMIC EVALUATION

The cost of biodiesel production, including feedstock, methanol and sodium hydroxide costs, was estimated for each feedstock using for the most part, a four and a half year history of prices (commencing in February 1999 – see Table A25 in the appendix and Figure 1). This period includes relatively low crop commodity prices (i.e. soybean oil prices) but is deemed representative of expected future prices for most of the commodities used in the analysis. An average price of $0.61/gal of methanol was used, a price that compares favorably with ethanol which may also be used for esterification (see Table A26 in the appendix).

Since all samples were produced using the same production method, analysis of energy and labor requirements, which would be similar across all feedstocks, was not performed. These energy and labor costs as well as capital costs of equipment are estimated to be relatively minor (approximately 15 cents per gallon, Tiffany (2001)) and may differ depending on plant location. For example, rendered chicken fat and vegetable oils may not require heating if converted to biodiesel immediately following rendering or hexane extraction. Should the plant be added to an existing processing plant, excess or waste heat from other production processes may also be used for esterification. Further, various subsidies exist for producers to recapture initial capital investment through the USDA Bioenergy program as well as state of Arkansas Biodiesel Incentive Acts 182 and 187. Thus, an analysis of energy, labor and capital costs is beyond the scope of this study.

Much more significant cost factors, compared to processing charges and capital costs of equipment, are feedstock cost, byproduct value/cost (glycerin and unreacted sludge) as well as methanol costs. Break-even biodiesel prices above the costs for methanol, sodium hydroxide and fat/oil were thus calculated for each feedstock with various assumptions about glycerin and sludge byproduct prices/costs to arrive at preliminary feedstock feasibility. For example, a biodiesel producer may face a feedstock cost of $0.20/lb and 7.7 lbs of oil are required to produce a gallon of biodiesel. If methanol and sodium hydroxide charges are $0.25/gallon of biodiesel produced, then that producer would need to recover at least $1.79/gallon if the glycerin and sludge byproducts do not generate revenue or incur disposal costs. By comparison, a cheaper feedstock might use more oil/fat, methanol and/or sodium hydroxide and thereby require a different breakeven price. It is these breakeven prices shown in Table 19 that are used for a preliminary comparison across different feedstocks.

The data of Table 19 suggest that chicken fat as a feedstock (as long as it is high yielding) would be preferred compared to the other feedstocks since it exhibits the lowest breakeven price. In order to assess what is driving the economic feasibility of various feedstocks, average input prices were used to remove market price impacts over time. As a first cut, the biodiesel yield and efficiency of methanol (ratio of required methanol to biodiesel produced) were examined. As stated previously, the efficiency of producing biodiesel appears to increase with higher levels of refinement in the oil or with improvements in yield potential in the chicken fat (an exception is refined soybean oil which is slightly more efficient than the refined, bleached soybean oil).

Table 19. Average of Biodiesel Yield, Input Use Efficiency, Ouput Ratios and Breakdown of Breakeven Biodiesel Price using Average Input Prices but Excluding non-Feedstock Processing Costs

	Volumetric Ratios					**Breakdown of Breakeven Biodiesel Price**		
Oil/Fat	Biodiesel Yield (Biodiesel : Oil/Fat)	Methanol Efficiency (Methanol : Biodiesel)	Glycerin Output (Glycerin : Biodiesel	Unreacted Material : Biodiesel	**Breakeven Biodiesel Price*** **($/gal)**	Oil/Fat ($/gal)	Methanol ($/gal)	**Oil/Fat Cost : Breakeven Biodiesel Price**
RBSO	0.88	0.27	0.16	0.10	1.87	1.70	0.17	0.91
RSO	0.86	0.25	0.16	0.07	1.81	1.66	0.16	0.91
DSO	0.88	0.28	0.19	0.09	1.74	1.56	0.18	0.90
CSO	0.77	0.34	0.40	0.05	1.91	1.70	0.21	0.89
RBRBO	0.86	0.23	0.14	0.10	na**	na	0.15	na
RRBO	0.74	0.28	0.25	0.20	na	na	0.18	na
CRBO	0.46	0.47	0.48	0.84	na	na	0.30	na
HYCF	0.83	0.31	0.21	0.09	1.17	0.98	0.20	0.83
LYCF	0.45	0.48	0.46	0.72	2.11	1.80	0.30	0.86

* Includes oil/fat, methanol and sodium hydroxide but no processing charges. It is not the final minimum consumer price at which biodiesel could be sold.

** Rice bran oil is only produced by a single company in the U.S. Public price information is therefore not available.

RBSO—Refined, bleached soybean oil (2 samples)
RSO—Refined soybean oil (2 samples)
DSO—Degummed soybean oil (2 samples)
CSO—Crude soybean oil (4 samples)
RBRBO—Refined, bleached rice bran oil (4 samples)
RRBO—Refined rice bran oil (3 samples)
CRBO—Crude rice bran oil (2 samples)
HYCF—High yield chicken fat (6 samples)
LYCF—Low yield chicken fat (5 samples)

Efficiency improvements in methanol are usually also accompanied by larger biodiesel yields (the amount of biodiesel produced per unit of oil/fat input). A natural question arises. Is it mostly biodiesel yield or methanol efficiency that drives biodiesel cost of production? Looking at the breakeven price column, the cheapest biodiesel for each of the different feedstocks is produced using degummed soybean oil and the high yielding chicken fat. These choices always correspond with the highest biodiesel yields within various types of feedstock (first column) and the lowest fat/oil cost component of the breakeven price. Note that methanol prices would have to more than quadruple before degummed soybean oil is no longer optimal. Feedstock price and biodiesel yield thus seem to determine the level of refinement of oil that would optimally be chosen for controlling the cost of production. Note further that differences in the cost of production across levels of refinement for soybean oil are much lower than those for chicken fat.

From a perspective of biodiesel yield, methanol efficiency and historical feedstock cost, the high yielding chicken fat thus appears to be the most promising feedstock for biodiesel production primarily because it is a relatively cheap raw material, has a high biodiesel yield and reasonable methanol efficiency. Since oil or fat raw material costs makes up a large percentage of overall biodiesel cost (ranging from 83 to 94% of the breakeven price as defined here), a natural extension to the discussion of economic feasibility of various feedstocks is the historical variability in prices of these raw materials and the associated biodiesel breakeven price. Highlighted in Figure 2 are breakeven prices of degummed soybean oil and high yielding chicken fat.

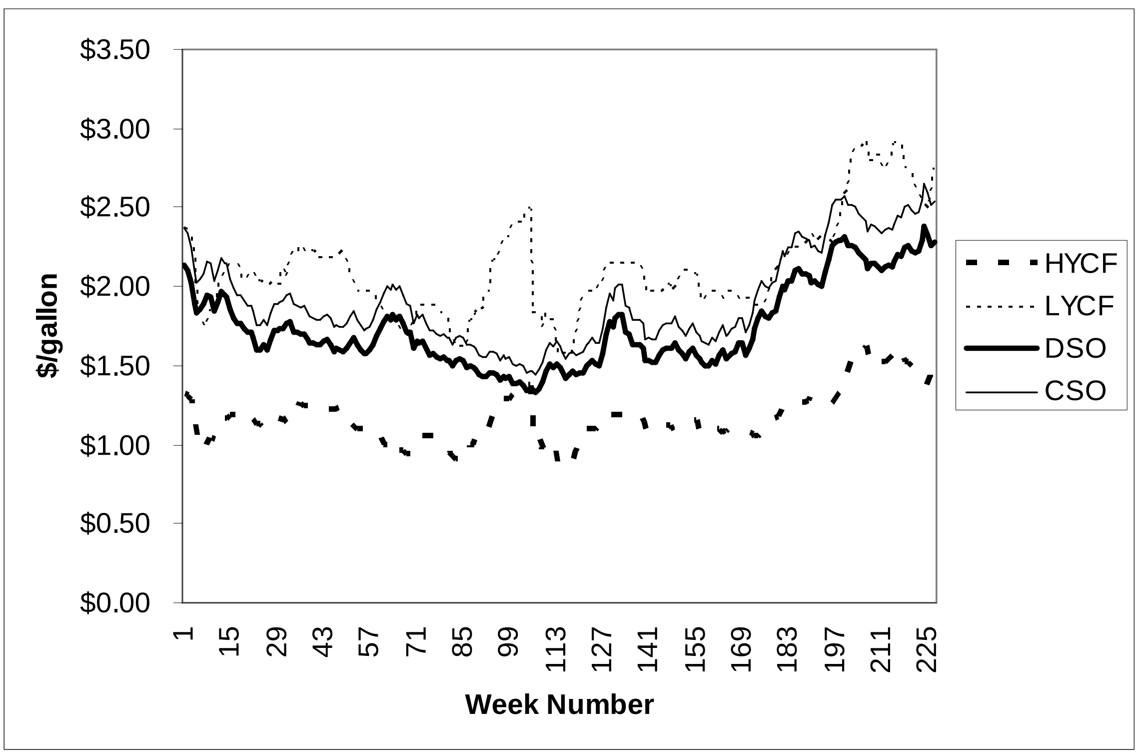


Figure 2. Weekly Biodiesel Breakeven Prices Using Average Material Balances, no Byproduct Value Consideration and Excluding non-Feedstock Processing Costs.

Note that the same input price for chicken fat is used for both low and high yielding chicken fat (two samples of chicken fat were sourced at different times with the low yielding chicken fat exposed to suboptimal storage conditions and the high yielding chicken fat processed within 4 hours of removal from the rendering facility). Variation in average material balances across chicken fat thus drives the differences in breakeven biodiesel cost at any point in time. Differences in soybean oil derived biodiesel are a function of both input price (for each level of refinement beyond crude oil, $0.01/lb is added to the cost of the raw material input) and some variation in material balances (note that fewer runs were performed on the soybean oils and only one sample was used for each soybean oil category) at any point in time. To what extent this inherent variation in material balances by feedstock is representative beyond the sampling done here should not only be investigated but may also change once production processes are optimized by changing catalysts, reaction times and temperatures.

Since variation in biodiesel cost over time is driven mainly by raw material prices for the fats and oils (as discussed above), decision makers interested in minimizing risk exposure to raw material price changes over time may be interested in producing biodiesel from several sources. While it is not a good idea to mix input before esterification or switch inputs frequently over time, it may be of interest to blend biodiesel from several plants to minimize exposure to input price risk and/or to meet biodiesel quality standards.

To examine the potential for minimizing price risk, cointegration tests were performed on the price series shown in Figure 1 to determine if fat and oil prices tend to covary over time in a systematic fashion. If price series are cointegrated they are said to respond to price shocks in a similar fashion over time. The analysis involves regressing each price series against each other and determining whether residuals exhibit a pattern. Statistical test results are not reported since all price series were cointegrated with the exception of soybean oil and lard. This suggests that fat and oil prices move in concert (this can also be observed in Figure 1 as there are very few crossing lines in the graphs) and thus little incentive exists to diversify among inputs for the purpose of reducing variation in biodiesel price. Choosing again, the optimal level of refinement among feedstocks, high yielding chicken fat offers slightly less risk (CV = 0.14, $\sigma = 0.17$) in biodiesel breakeven price compared to degummed soybean oil (CV = 0.15, $\sigma = 0.26$). Soybean oil, however, offers the potential for managing price risk through use of hedging as futures and options can be traded. Similar hedging options are not available for chicken fat and thus long term contractual arrangements may be preferable.

Up to this point, quality standards as well as byproduct disposal cost/revenue potential have been ignored for the economic evaluation. With respect to quality standards, the blending of biodiesels (generated from different feedstock sources) presents an opportunity to attain quality thresholds without modifying production methods. Of the eight quality tests performed only the sulfated ash test lends itself to blending as other standards either do not blend (e.g. cloud point), blend to an unknown extent (e.g. viscosity) or insufficient information is available (e.g. cetane number and lubricity). Solving for least-cost biodiesel blends using linear programming to meet the sulfated ash standard of less than 0.02% by weight resulted in an optimal mix of 42% high yielding chicken fat and 58% degummed soybean oil. The 1999-2003 average, blended final biodiesel breakeven price was $1.50/gal with a CV of 14% and $\sigma = 0.21$ using average material balances presented in Table 9.

Taking glycerin and unreacted material into consideration resulted in somewhat surprisingly small changes in the least-cost blend across a number of scenarios presented in Table 20. The first scenario (no byproduct consideration) imposes the sulfated ash standard and the least cost biodiesel blend costs $1.50/gal compared to a least cost of $1.17/gal using the lowest cost feedstock alone (high yield chicken fat). Adding an average glycerin price of $0.77/lb (the second scenario entitled glycerin – market price in Table 20) modifies the optimal blend to using low yielding chicken fat as a large amount of glycerin is produced with biodiesel cost lowered dramatically (biodiesel from low yielding chicken fat is assumed to have the same sulfated ash content as biodiesel from high yielding chicken fat). This result is somewhat questionable for two reasons: i) the quality of glycerin was not measured across feedstocks and therefore an assumption of market price may be unreasonable (hence the third scenario entitled glycerin – low output shows at what glycerin price level high yielding chicken fat re-enters the least-cost biodiesel blend); and ii) glycerin output, as a result of biodiesel production, can be very voluminous and thus glycerin may become a disposal problem rather than a revenue generating venture once a large amount of biodiesel production generates supply pressure on glycerin prices (the fourth scenario depicts a disposal cost situation). Should unreacted material and glycerin incur disposal costs estimated at $30/ton due to the non-toxic nature of the product, the final production cost of biodiesel is impacted only very marginally at $0.03/gal. Further, glycerin and/or unreacted material may be used as ingredients in livestock feed rations.

Table 20. Biodiesel Cost, Glycerin Byproduct Value and Unreacted Material Disposal Costs per Gallon of Biodiesel Produced under Various Market Conditions using Average Material Balance and Feedstock Costs.

Scenario	CF*	Biodiesel Cost** ($/gal)	Glycerin			Unreacted Material	
			Price ($/lb)	Production (lb/gal)	Value ($/gal)	Production (lb/gal)	Cost ($/gal)
No Byproduct Consideration	HY	1.50	0.00	1.38	na	0.63	na
Glycerin – Market Price	LY	0.85 to 0.18	0.47 to 0.77	2.23	1.05 to 1.72	2.52	na
Glycerin – Low Output	HY	0.87 to 1.50	0.46 to 0.00	1.38	0.00 to 0.63	0.63	na
Disposal Cost	HY	1.53	-0.015	1.38	-0.02	0.63	-0.01

* Least-cost biodiesel blends consisted of 58% of biodiesel produced from degummed soybean oil and 42% of chicken fat regardless of scenario. The column indicates whether high yield (HY) or low yield (LY) chicken fat is used.

** The range of biodiesel cost estimates corresponds with the glycerin price range (i.e. $0.85 biodiesel cost corresponds with $0.47 glycerin price and $1.05 byproduct value contribution to biodiesel cost for the Glycerin – Market Price scenario).

Finally, optimization of production methods may also lead to reductions in potentially undesirable byproducts especially in large operations (note the amount of byproduct production for various size plants in Table 21 for the scenarios depicted in Table 20). Annual disposal costs under the disposal cost scenario would certainly justify additional research in modifying processing technology or finding ways to potentially feed byproducts to livestock or generate energy from byproducts.

Table 21. Byproduct Implications under Various Market Conditions and Plant Sizes.

Scenario	Plant Size (Millions of Gallons of Biodiesel per Year)					
	5	15	30	5	15	30
	Annual Disposal Costs (in $ 000s)			Tons of Unreacted Material		
No Byproduct Consideration				1433	4299	8598
Glycerin – Market Price	na	na	na	5718	17155	34311
Glycerin – Low Output				1433	4299	8598
Disposal Cost	43	129	258	1433	4299	8598
	Annual Glycerin Sales (in $ 000s)			Trucks per Week*		
No Byproduct Consideration	na	na	na	3	8	17
Glycerin - Market Price ($0.77/lb)	8576	25727	51454	4	13	27
Glycerin - Low Output ($0.46/lb)	3176	9528	19057	3	8	17
Disposal Cost	-104	-311	-621	3	8	17

* Assumes a 50,000 lb truck payload and 50 weeks of production per year.

CONCLUSIONS

The results of this study show that biodiesel can be produced from a variety of vegetable oil/animal fat feedstocks of varying quality, producing B100 biodiesel that, in general, satisfies ASTM requirements. Although the single biodiesel production protocol that was followed for each of the feedstocks will not necessarily optimize biodiesel yield, the single protocol does represent a method for easily comparing the economics of producing biodiesel from these feedstocks.

Material balance calculations show that, as the quality of the oil/fat increases, the yield of biodiesel increases as well. At the same time, less methanol is required for reaction and less glycerin and unreacted material are produced. As an example, an average of 130 ml of biodiesel, 17.61 g of glycerin and 13 ml of unreacted material were produced from 150 ml of refined, bleached rice bran oil and 30.3 ml of methanol. By contrast, an average of 69 ml of biodiesel, 30.71 g of glycerin and 58 ml of unreacted material were produced from 150 ml of crude rice bran oil and 32.8 ml of methanol. Refined, bleached soybean oil, degummed soybean oil, refined, bleached rice bran oil and high yield chicken fat produced the most biodiesel, yielding an average of 0.88 ml of biodiesel per ml of oil/fat.

In performing a variety of ASTM tests on the biodiesel samples, all of the samples tested met the standards for cetane number (only two samples tested), heat of combustion (Mead Biofuel lower heating value standard), cloud point (with assumptions), and copper corrosion. No standard exists for lubricity, although a major feature of biodiesel is its ability to yield increased lubricity. Only some of the samples met the standards for kinematic viscosity, flash point and sulfated ash. It is believed that perhaps a better job of preparing the biodiesels would have led to the samples also meeting these standards, but this has not been substantiated.

The economic evaluation revealed that biodiesel yield in conjunction with raw material input price drives the selection of level of refinement for vegetable oils and the ultimate biodiesel cost. Methanol efficiency (the ratio of required methanol to biodiesel produced) by contrast, affects biodiesel cost only marginally. Processing charges, energy, labor and transportation costs were only discussed but not analyzed. Imposing ASTM quality standards resulted in a least-cost biodiesel blend involving degummed soybean oil and chicken fat. The material balances associated with chicken fat suggest a wide range of biodiesel production costs that may lend themselves useful pending market conditions for byproducts. Analysis of input price risk management strategies revealed the importance of access to organized exchanges for utilizing futures and options for hedging. Chicken fat is an attractive feedstock from the perspective of low cost and low input price risk. Since fats and oils tend to respond to demand and supply fluctuations in a similar fashion (price series are cointegrated), little incentive exists to diversify operations from a perspective of managing input price risk by using several feedstocks. Byproduct value and/or disposal cost implications can be very large especially for larger operations. Further refinement in production processing methodology and additional testing on the type of variation in material balances that may be apparent with different feedstocks are required to provide more explicit recommendations about plant location on the basis of least-cost inputs. The value of glycerin byproduct plays a much larger role than potential disposal costs.

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APPENDIX

Table A1. Preliminary Material Balances (cont'd next page)

Oil/Fat	ml Oil Treated	g NaOH Required	ml Methanol Fed	ml Glycerin Produced	ml Biodiesel Produced	ml Methanol Used/lost
RBSO	150	1.1	100	46	71.5	88.5
RBSO	150	1	75	48	132	68
RBSO	150	0.5	75	41	134	68.6
RBSO	150	1.5	75	59	99.5	65.4
RBSO	150	0.25	75.5	43	133	63.5
RBSO	150	0.125	75.25	46	146	63.25
RBSO	150	1	75	55	138	64.5
RBSO	150	1	75	54.5	138	65
RSO	150	0.5	75	50	126	69
RSO	150	1	75	62.5	132	67
RSO	150	1.3	75	58	98	64
RSO	150	1.3	75	58	108	62.2
RSO	150	1.3	75	56	120	64
RSO	150	1.3	75	60	134	64.8
RSO	150	1	75	56	130	68
RSO	150	1	75	59	-	-
RSO	150	0.75	75	51	141	65
RSO	150	0.75	75	54	138	63.5
RSO	150	0.5	75	50	137	65
RSO	150	0.5	75	51.5	-	69
RSO	150	0.25	75	41	131	62
RSO	150	0.25	75	53	137	63.5
DSO	150	1.3	75	56	138	65.4
DSO	150	1.3	75	60	120	63
DSO	150	1.3	75	62	112	66
DSO	150	1.3	75	60	118	65
DSO	150	1.3	75	66	90	62.8
DSO	150	1.3	75	64	82	63
DSO	150	1.3	75	59	112	65.6
DSO	150	1.3	75	64	102	64.4
DSO	150	1.25	75	57	118	62
DSO	150	1.25	75	61	130	67
DSO	150	1.25	75	65	106	63
DSO	150	1.25	75	65	117	64
DSO	150	1	75	62	126	65.5
DSO	150	1	75	58	134	66
RBRBO	150	1.3	75	54	120	63.6
RBRBO	150	1.3	75	55	140	66.6
RBRBO	150	1.3	75	59	112	66.2
RBRBO	150	1.3	75	57	119	66.6
RBRBO	150	1.25	87	71.5	108	74.5

Oil/Fat	ml Oil Treated	g NaOH Required	ml Methanol Fed	ml Glycerin Produced	ml Biodiesel Produced	ml Methanol Used/lost
RBRBO	150	1.25	87	71.5	116	73.8
RBRBO	150	1.25	75	62	-	-
RBRBO	150	1.25	75	66	83	65
RBRBO	150	1	75	56	145	63
RBRBO	150	1	75	54	112	65
RBRBO	150	0.75	75	60	117	62.5
RBRBO	150	0.75	75	51	132	65
RBRBO	150	0.75	75	56	130	64.5
RBRBO	150	0.75	75	53	119	63.5
RBRBO	150	0.5	75	52	135	64
RBRBO	150	0.5	75	53	128	61.5
RBRBO	150	0.5	75	54	140	67.5
RBRBO	150	0.5	75	53	146	69
RRBO	150	1.3	75	60	70	63.8
RRBO	150	1.3	75	66	87.5	63.8
RRBO	150	1.3	75	58	86	65.2
RRBO	150	1.3	75	61	82	64.6
RRBO	150	1.25	75	56	87	62.8
RRBO	150	1.25	75	55	114	63.2
CRBO	150	1.25	75	77	82	66.5
CRBO	150	1.25	75	77	66	66.5
CRBO	150	1	85	79	70	72
CRBO	150	1	85	87	90	73.5
CRBO	150	0.75	75	152	-	-
CRBO	150	0.75	75	180	-	-
CRBO	150	1.25	75	75	56	134
CRBO	150	1.25	75	72	72	140

RBSO—Refined, bleached soybean oil
RSO—Refined soybean oil
DSO—Degummed soybean oil
RBRBO—Refined, bleached rice bran oil
RRBO—Refined rice bran oil
CRBO-Crude rice bran oil

Table A2. Material Balances with Methanol Also Recovered from Glycerin

Oil/Fat	ml Oil Treated	g NaOH Required	ml Methanol Fed	g Glycerin Produced	ml Biodiesel Produced	ml Methanol Recovered	ml Sludge Produced
RBSO	150	0.75	75	17.30	142	37	6
RBSO	150	0.75	75	16.63	122	42	20
RSO	150	1	75	16.17	127	42.5	7
RSO	150	1	75	17.23	131	44	12
DSO	150	1	75	24.36	130	37.5	10
DSO	150	1	75	19.07	134	37.5	13
CSO	150	1	75	22.73	126	34	8
CSO	150	1	75	49.09	102	39	3
CSO	150	1	75	34.34	122	34.5	4
CSO	150	1	75	41.23	113	39	7
RBRBO	150	0.75	75	17.51	137	45.5	5
RBRBO	150	0.75	75	17.82	122	48	16
RBRBO	150	0.75	75	16.04	126	41	20
RBRBO	150	0.75	75	19.06	133	44.5	11
RRBO	150	1.25	75	23.36	101	48	31
RRBO	150	1.25	75	23.03	104	45.5	29
RRBO	150	1	75	27.04	128	37	6
CRBO	150	1	75	33.16	52	44.5	68
CRBO	150	1	75	28.26	86	40	48
LYCF	150	1	75	30.62	49	42.5	66
LYCF	150	1	75	25	64	42	54
LYCF	150	1	75	27.24	75	40.5	47
LYCF	150	1	75	29.97	58	42	53
LYCF	150	1	75	26.21	94	44.5	24
HYCF	150	1	75	23.38	108	38.5	20
HYCF	150	1	75	18.34	128	39.5	5
HYCF	150	1	75	24.92	129	32	7
HYCF	150	1	75	15.67	130	33	12
HYCF	150	1	75	20.07	127	37	13
HYCF	150	1	75	22.76	128	36.5	10

RBSO—Refined, bleached soybean oil
RSO—Refined soybean oil
DSO—Degummed soybean oil
CSO—Crude soybean oil
RBRBO—Refined, bleached rice bran oil
RRBO—Refined rice bran oil
CRBO—Crude rice bran oil
LYCF—Low yield chicken fat
HYCF—High yield chicken fat

Table A3. IQT™ Test Results of Cetane Number*

Sample	IQT DCN Test 1	Test 2	Test 3	Average
Refined, bleached soybean oil	55.0	55.7	56.1	55.6
High yield chicken fat	59.4	59.6		59.5

*Performed by AET using the ASTM D6890-03 test method

Table A4. BOTD Lubricity Test Results*

Sample	Avg. Wear Scar Diameter (µm)
Refined, bleached soybean oil	371.7
High yield chicken fat	370.2

*Performed by AET

Table A5. Kinematic Viscosity Data

Biodiesel sample	1st Run (sec)	2nd Run (sec)	3rd Run (sec)	Average (sec)	Viscosity (cS)	Density (g/cm^3)	Viscosity (cP)
Refined, bleached soybean oil	419.00	427.00	435.00	427.00	**6.41**	0.888	**5.69**
Refined soybean oil	439.00	443.00	433.00	438.33	**6.58**	0.885	**5.82**
Degummed soybean oil	450.00	449.00	452.00	450.33	**6.76**	0.892	**6.03**
Crude soybean oil	387.00	388.00	387.00	387.30	**5.81**	0.872	**5.07**
Refined, bleached rice bran oil	475.00	477.00	473.00	475.00	**7.13**	0.874	**6.23**
Refined rice bran oil	505.00	500.00	496.00	500.33	**7.51**	0.878	**6.59**
Crude rice bran oil	555.00	562.00	572.00	563.00	**8.45**	0.887	**7.49**
High yield chicken fat	426.00	426.00	428.00	426.67	**6.40**	0.858	**5.49**

Table A6. Flash Point Data for Biodiesel Produced from Refined, Bleached Soybean Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	300	148.9	Y
2	295	146.1	Y
3	293	145.0	Y
4	290	143.3	Y
5	285	140.6	Y
6	280	137.8	Y
7	275	135.0	N
8	270	132.2	N
9	265	129.4	N
10	260	126.7	N
11	255	123.9	N
12	250	121.1	N
13	245	118.3	N
14	240	115.6	N
15	235	112.8	N

Table A7. Flash Point Data for Biodiesel Produced from Refined Soybean Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	298	147.8	Y
2	295	146.1	Y
3	300	148.9	Y
4	290	143.3	Y
5	285	140.6	Y
6	280	137.8	Y
7	277	136.1	Y
8	275	135.0	Y
9	270	132.2	N
10	265	129.4	N
11	260	126.7	N

Table A8. Flash Point Data for Biodiesel Produced from Degummed Soybean Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	290	143.3	Y
2	285	140.6	Y
3	270	132.2	Y
4	265	129.4	Y
5	260	126.7	Y
6	255	123.9	Y
7	250	121.1	Y
8	245	118.3	Y
9	240	115.6	N
10	235	112.8	N
11	230	110.0	N
12	225	107.2	N

Table A9. Flash Point Data for Biodiesel Produced from Crude Soybean Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	300	148.9	Y
2	290	143.3	Y
3	280	137.8	Y
4	270	132.2	Y
5	260	126.7	Y
6	250	121.1	Y
7	240	115.6	Y
8	230	110.0	Y
9	220	104.4	Y
10	210	98.9	Y
11	200	93.3	Y
12	190	87.8	Y
13	180	82.2	Y
14	170	76.7	N
15	160	71.1	N

Table A10. Flash Point Data for Biodiesel Produced from Refined, Bleached Rice Bran Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	260	126.7	Y
2	255	123.9	Y
3	250	121.1	Y
4	245	118.3	Y
5	240	115.6	N
6	235	112.8	N
7	230	110.0	N

Table A11. Flash Point Data for Biodiesel Produced from Refined Rice Bran Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	305	151.7	Y
2	300	148.9	Y
3	280	137.8	Y
4	275	135.0	Y
5	270	132.2	Y
6	265	129.4	Y
7	260	126.7	N
8	255	123.9	N
9	250	121.1	N
10	245	118.3	N
11	240	115.6	N

Table A12. Flash Point Data for Biodiesel Produced from Crude Rice Bran Oil

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	270	132.2	Y
2	265	129.4	Y
3	260	126.7	Y
4	255	123.9	Y
5	250	121.1	Y
6	245	118.3	Y
7	240	115.6	N
8	235	112.8	N
9	230	110.0	N

Table A13. Flash Point Data for Biodiesel Produced from High Yield Chicken Fat

Run	Temp (°F)	Temp (°C)	Flash (y/n)
1	300	148.9	Y
2	290	143.3	Y
3	280	137.8	Y
4	270	132.2	Y
5	260	126.7	Y
6	250	121.1	Y
7	240	115.6	Y
8	230	110.0	Y
9	220	104.4	Y
10	210	98.9	Y
11	200	93.3	Y
12	190	87.8	Y
13	180	82.2	Y
14	170	76.7	Y
15	160	71.1	N
16	150	65.6	N

Table A14. Heat of Combustion Data

Sample	Sample Mass (g)	TINITIAL (degrees C)	TFINAL (degrees C)	Temp Rise	Fuse Correction (calories)	Mass of Soot (g)	Gross Heat of Combustion (calories per gram)	Gross Heat of Combustion (BTU's per pound)
RB-SO Bulk 4	0.4284	24.321	26.007	1.686	3	0.003	9517.09	17,128.57
RB-SO Bulk 3	0.5507	25.418	27.571	2.153	3	0.0006	9455.71	17,018.10
RB-SO Bulk 1	0.5971	23.775	26.124	2.349	4	0.0013	9513.62	17,122.32
R-SO Bulk 2	0.5469	25.22	27.356	2.136	1	0.0035	9449.84	17,007.55
R-SO Bulk 2	0.5135	25.602	27.606	2.004	4	0.0028	9436.57	16,983.66
D-SO Bulk 3	0.516	23.981	25.993	2.012	2	0.0189	9432.25	16,975.88
D-SO Bulk 3	0.4923	24.759	26.684	1.925	1	0.0097	9460.69	17,027.07
D-SO Bulk 3	0.5327	23.008	25.088	2.08	5	0.0066	9439.83	16,989.53
D-SO Bulk 3	0.5504	24.374	26.517	2.143	6	0.0016	9411.45	16,938.44
RB-RBO Bulk 2	0.5142	25.625	27.64	2.015	3	0.0041	9477.44	17,057.21
RB-RBO Bulk 2	0.5189	26.599	28.632	2.033	6	0.0023	9469.76	17,043.40
RB-RBO Bulk 2	0.5184	24.012	26.021	2.009	2	0.0069	9374.58	16,872.08
R-RBO Bulk 1	0.535	25.051	27.182	2.131	5	0.0048	9629.94	17,331.68
R-RBO Bulk 1	0.5412	23.058	25.197	2.139	3	0.0006	9559.09	17,204.17
R-RBO Bulk 1	0.5963	24.269	26.618	2.349	3	0.003	9528.06	17,148.31
C-RBO Bulk 1	0.5121	23.678	25.691	2.013	3	0.0039	9506.85	17,110.15
C-RBO Bulk 1	0.5024	25.741	27.713	1.972	5.2	0.0028	9488.54	17,077.18
C-RBO Bulk 1	0.5042	26.544	28.506	1.962	7	0.0027	9403.09	16,923.41
CKO	0.502	23.313	25.27	1.957	6	0.0007	9422.19	16,957.78
CKO Bulk 3	0.5028	24.209	26.184	1.975	4.5	0.0017	9496.82	17,092.09
CKO Bulk 3	0.5032	25.186	27.153	1.967	6	0.0022	9447.81	17,003.89
CSO	0.5002	23.492	25.475	1.983	6	0.0004	9581.89	17,245.19
CSO	0.4993	24.657	26.382	1.725	6	0.0011	8348.69	15,025.72

Table A15. Cloud Point Data for Biodiesel Produced from Refined, Bleached Soybean Oil

Run	Temp (°C)	Cloud (y/n)
1	12.0	N
2	6.0	N
3	5.0	N
4	1.0	N
5	0.0	N
6	-1.0	Y

Table A16. Cloud Point Data for Biodiesel Produced from Refined Soybean Oil

Run	Temp (°C)	Cloud (y/n)
1	13.0	N
2	10.0	N
3	5.0	N
4	3.0	N
5	1.0	N
6	0.0	Y

Table A17. Cloud Point Data for Biodiesel Produced from Degummed Soybean Oil

Run	Temp (°C)	Cloud (y/n)
1	7.0	N
2	4.5	N
3	4.0	N
4	3.0	N
5	2.0	N
6	1.0	N
7	0.0	N
8	-1.0	N
9	-2.0	N

Could not lower temperature below -2°C

Table A18. Cloud Point Data for Biodiesel Produced from Crude Soybean Oil

Run	Temp (°C)	Cloud (y/n)
1	12.0	N
2	7.0	N
3	5.0	N
4	3.0	N
5	0.0	N
6	-1.0	N
7	-2.0	N

Could not lower temperature below -2°C

Table A19. Cloud Point Data for Biodiesel Produced from Refined, Bleached Rice Bran Oil

Run	Temp (°C)	Cloud (y/n)
1	14.0	N
2	9.0	N
3	8.0	N
4	5.0	N
5	3.0	N
6	1.0	N
7	0.0	Y

Table A20. Cloud Point Data for Biodiesel Produced from Refined Rice Bran Oil

Run	Temp (°C)	Cloud (y/n)
1	13.0	N
2	8.0	N
3	7.0	N
4	5.0	N
5	4.0	N
6	3.0	N
7	2.0	Y

Table A21. Cloud Point Data for Biodiesel Produced from Crude Rice Bran Oil

Run	Temp (°C)	Cloud (y/n)
1	11.0	N
2	9.0	N
3	6.0	N
4	4.0	N
5	3.0	N
6	0.0	N
7	-1.0	N

Could not lower temperature below -2°C

Table A22. Cloud Point Data for Biodiesel Produced from High Yield Chicken Fat

Run	Temp (°C)	Cloud (y/n)
1	19.5	N
2	18.0	N
3	15.0	N
4	14.0	N
5	12.0	N
6	11.0	N
7	10.0	N
8	9.0	N
9	7.0	N
10	6.0	N
11	5.0	Y
12	4.5	Y
13	4.0	Y

Table A23. Sulfated Ash Data

Biodiesel sample	Sample (g)	Sulfated Ash (g)	Sulfated Ash Mass Percent
Refined, bleached soybean oil	36.6266	0.0035	0.0096%
Refined soybean oil	442.1775	0.0062	0.0014%
Degum soybean oil	35.0660	0.0004	0.0011%
Crude soybean oil	34.1546	0.0242	0.0709%
Refined, bleached rice bran oil	32.6198	0.0047	0.0144%
Refined rice bran oil	30.1445	0.0140	0.0464%
Crude rice bran oil	34.0700	0.0413	0.1212%
Chicken Fat	32.9112	0.0152	0.0462%

Table A24. Copper Corrosion Data

Biodiesel sample	Corrosion Category
Refined, bleached soybean oil	1 a
Refined soybean oil	1 a
Degummed soybean oil	1 a
Crude soybean oil	1 a
Refined, bleached rice bran oil	1 a
Refined rice bran oil	1 a
Crude rice bran oil	1 a
Chicken fat	1 a

Table A25. Weekly Feedstock Prices in $/lb (February, 1999 to June, 2003).
(continued next 4 pages)

Week#	Pet Grade Chicken Fat	Feed Grade Chicken Fat	Tallow (Chicago)	Lard (Chicago)	Soybean Oil (Decatur)	Corn Oil (Decatur)
1	0.1181	0.1150	0.1350	0.1430	0.2123	0.2833
2	0.1175	0.1125	0.1335	0.1400	0.2092	0.2783
3	0.1150	0.1100	0.1225	0.1419	0.2001	0.2722
4	0.1050	0.0975	0.1025	0.1380	0.1852	0.2423
5	0.0875	0.0825	0.0905	0.1140	0.1779	0.2295
6	0.0863	0.0725	0.0900	0.1100	0.1804	0.2308
7	0.0825	0.0713	0.0960	0.1180	0.1841	0.2313
8	0.0838	0.0775	0.1090	0.1290	0.1915	0.2288
9	0.0888	0.0813	0.1150	0.1300	0.1900	0.2288
10	0.0875	0.0725	0.1175	0.1344	0.1792	0.2291
11	0.0950	0.0788	0.1155	0.1315	0.1866	0.2300
12	0.1000	0.0800	0.1155	0.1300	0.1941	0.2305
13	0.1025	0.0850	0.1095	0.1300	0.1909	0.2340
14	0.1025	0.0800	0.1025	0.1300	0.1901	0.2350
15	0.1050	0.0825	0.0992	0.1315	0.1807	0.2303
16	0.1050	0.0800	0.1090	0.1355	0.1751	0.2270
17	0.1050	0.0744	0.1060	0.1380	0.1707	0.2268
18	0.1000	0.0744	0.1113	0.1400	0.1706	0.2300
19	0.1000	0.0813	0.1175	0.1380	0.1671	0.2300
20	0.1000	0.0800	0.1200	0.1330	0.1643	0.2288
21	0.1025	0.0813	0.1210	0.1220	0.1641	0.2290
22	0.1025	0.0825	0.1227	0.1160	0.1603	0.2300
23	0.0988	0.0850	0.1269	0.1100	0.1520	0.2291
24	0.0988	0.0838	0.1260	0.1120	0.1521	0.2250
25	0.0975	0.0900	0.1300	0.1200	0.1558	0.2240
26	0.0975	0.0850	0.1300	0.1300	0.1514	0.2220
27	0.0975	0.0775	0.1202	0.1335	0.1595	0.2223
28	0.0988	0.0788	0.1227	0.1365	0.1651	0.2238
29	0.0988	0.0819	0.1300	0.1390	0.1650	0.2243
30	0.0975	0.0825	0.1335	0.1400	0.1664	0.2250
31	0.1038	0.0825	0.1370	0.1495	0.1676	0.2245

Week#	Pet Grade Chicken Fat	Feed Grade Chicken Fat	Tallow (Chicago)	Lard (Chicago)	Soybean Oil (Decatur)	Corn Oil (Decatur)
32	0.1000	0.0825	0.1394	0.1581	0.1707	0.2216
33	0.1063	0.0875	0.1540	0.1650	0.1722	0.2200
34	0.1100	0.0856	0.1620	0.1820	0.1649	0.2200
35	0.1088	0.0857	0.1650	0.1980	0.1638	0.2203
36	0.1125	0.0875	0.1655	0.2000	0.1630	0.2200
37	0.1100	0.0900	0.1680	0.2020	0.1637	0.2200
38	0.1100	0.0925	0.1620	0.2090	0.1598	0.2200
39	0.1100	0.0950	0.1600	0.2100	0.1572	0.2188
40	0.1100	0.0950	0.1540	0.2100	0.1563	0.2193
41	0.1075	0.0950	0.1480	0.1950	0.1554	0.2193
42	0.1075	0.0944	0.1510	0.1650	0.1549	0.2200
43	0.1075	0.0944	0.1463	0.1550	0.1578	0.2200
44	0.1075	0.0944	0.1500	0.1560	0.1589	0.2200
45	0.1075	0.0931	0.1535	0.1600	0.1561	0.2190
46	0.1075	0.0931	0.1395	0.1600	0.1506	0.2163
47	0.1075	0.0931	0.1260	0.1620	0.1524	0.2153
48	0.1088	0.0950	0.1300	0.1650	0.1514	0.2134
49	0.1100	0.0950	0.1325	0.1680	0.1508	0.2103
50	0.1050	0.0925	0.1230	0.1655	0.1534	0.2073
51	0.1000	0.0925	0.1125	0.1550	0.1570	0.2075
52	0.0975	0.0900	0.1100	0.1430	0.1609	0.2075
53	0.0950	0.0888	0.0910	0.1270	0.1553	0.2048
54	0.0950	0.0888	0.1035	0.1250	0.1515	0.2038
55	0.0950	0.0813	0.1050	0.1240	0.1490	0.2003
56	0.0950	0.0969	0.1050	0.1225	0.1496	0.1950
57	0.0950	0.0863	0.1050	0.1205	0.1513	0.1938
58	0.0950	0.0800	0.1080	0.1225	0.1549	0.1928
59	0.0913	0.0813	0.1100	0.1225	0.1615	0.1925
60	0.0900	0.0738	0.1080	0.1225	0.1666	0.1928
61	0.0850	0.0675	0.1020	0.1105	0.1714	0.1928
62	0.0850	0.0663	0.1010	0.1205	0.1760	0.1910
63	0.0850	0.0644	0.1050	0.1180	0.1736	0.1813
64	0.0850	0.0644	0.1025	0.1200	0.1776	0.1759
65	0.0875	0.0644	0.1000	0.1200	0.1739	0.1745
66	0.0813	0.0625	0.1082	0.1200	0.1764	0.1738
67	0.0813	0.0625	0.1125	0.1240	0.1707	0.1730
68	0.0788	0.0700	0.1175	0.1300	0.1648	0.1665
69	0.0788	0.0713	0.1220	0.1300	0.1638	0.1595
70	0.0850	0.0738	0.1250	0.1350	0.1536	0.1508
71	0.0875	0.0750	0.1220	0.1330	0.1586	0.1500
72	0.0900	0.0750	0.1112	0.1270	0.1561	0.1473
73	0.0900	0.0750	0.0965	0.1220	0.1583	0.1438
74	0.0900	0.0750	0.0930	0.1200	0.1526	0.1408
75	0.0900	0.0750	0.0900	0.1125	0.1484	0.1378
76	0.0900	0.0750	0.0920	0.1030	0.1485	0.1358
77	0.0900	0.0688	0.0925	0.1000	0.1462	0.1353
78	0.0875	0.0650	0.0925	0.1000	0.1454	0.1343
79	0.0875	0.0650	0.0925	0.1015	0.1460	0.1345
80	0.0850	0.0663	0.0925	0.1025	0.1437	0.1348
81	0.0800	0.0550	0.0945	0.1030	0.1439	0.1303

Week#	Pet Grade Chicken Fat	Feed Grade Chicken Fat	Tallow (Chicago)	Lard (Chicago)	Soybean Oil (Decatur)	Corn Oil (Decatur)
82	0.0775	0.0563	0.0970	0.1050	0.1401	0.1270
83	0.0750	0.0538	0.0985	0.1050	0.1443	0.1235
84	0.0750	0.0525	0.1006	0.1075	0.1449	0.1213
85	0.0750	0.0525	0.0980	0.1100	0.1443	0.1203
86	0.0750	0.0600	0.0992	0.1115	0.1395	0.1180
87	0.0850	0.0650	0.1047	0.1170	0.1404	0.1155
88	0.0850	0.0688	0.1060	0.1220	0.1385	0.1125
89	0.0875	0.0663	0.1050	0.1295	0.1379	0.1063
90	0.0900	0.0700	0.1030	0.1320	0.1334	0.1025
91	0.0888	0.0788	0.0930	0.1350	0.1325	0.1018
92	0.0950	0.0863	0.0870	0.1310	0.1323	0.1023
93	0.0950	0.0963	0.0940	0.1180	0.1352	0.1038
94	0.1063	0.0950	0.0940	0.1110	0.1353	0.1028
95	0.1063	0.0950	0.0944	0.1100	0.1342	0.1034
96	0.1100	0.1025	0.0972	0.1145	0.1300	0.1055
97	0.1150	0.0938	0.1055	0.1195	0.1330	0.1050
98	0.1150	0.0913	0.1117	0.1210	0.1310	0.1045
99	0.1150	0.0900	0.1170	0.1225	0.1323	0.1065
100	0.1200	0.0969	0.1188	0.1250	0.1274	0.1063
101	0.1200	0.1025	0.1225	0.1275	0.1269	0.1063
102	0.1200	0.1025	0.1290	0.1350	0.1281	0.1023
103	0.1200	0.1038	0.1281	0.1400	0.1268	0.1000
104	0.1250	0.1063	0.1177	0.1400	0.1222	0.1008
105	0.1250	0.1100	0.1040	0.1340	0.1237	0.1055
106	0.0875	0.0988	0.0970	0.1257	0.1236	0.1095
107	0.0875	0.0988	0.0935	0.1170	0.1211	0.1100
108	0.0875	0.0988	0.0944	0.1125	0.1242	0.1119
109	0.0825	0.0863	0.0895	0.1105	0.1289	0.1145
110	0.0875	0.0825	0.0975	0.1075	0.1369	0.1150
111	0.0850	0.0800	0.0985	0.1095	0.1409	0.1175
112	0.0850	0.0825	0.0980	0.1100	0.1389	0.1225
113	0.0725	0.0788	0.0935	0.1140	0.1418	0.1220
114	0.0725	0.0788	0.0957	0.1190	0.1392	0.1285
115	0.0725	0.0788	0.1000	0.1219	0.1359	0.1350
116	0.0725	0.0788	0.1062	0.1225	0.1315	0.1405
117	0.0725	0.0775	0.1075	0.1225	0.1342	0.1445
118	0.0725	0.0775	0.1025	0.1210	0.1358	0.1430
119	0.0800	0.0775	0.0982	0.1200	0.1337	0.1440
120	0.0875	0.0750	0.0987	0.1200	0.1349	0.1465
121	0.0938	0.0763	0.1037	0.1155	0.1350	0.1525
122	0.0950	0.0763	0.1100	0.1150	0.1404	0.1550
123	0.0950	0.0813	0.1140	0.1165	0.1415	0.1575
124	0.0950	0.0813	0.1240	0.1250	0.1443	0.1610
125	0.0950	0.0825	0.1275	0.1355	0.1411	0.1595
126	0.0975	0.0825	0.1310	0.1460	0.1408	0.1600
127	0.0975	0.0825	0.1375	0.1581	0.1494	0.1625
128	0.1050	0.0825	0.1405	0.1680	0.1629	0.1685
129	0.1050	0.0825	0.1520	0.1930	0.1716	0.1765
130	0.1050	0.0875	0.1750	0.2050	0.1679	0.1790
131	0.1050	0.0888	0.1760	0.2050	0.1746	0.1838

Week#	Pet Grade Chicken Fat	Feed Grade Chicken Fat	Tallow (Chicago)	Lard (Chicago)	Soybean Oil (Decatur)	Corn Oil (Decatur)
132	0.1050	0.0900	0.1685	0.2180	0.1771	0.1885
133	0.1050	0.0950	0.1655	0.2360	0.1777	0.1920
134	0.1050	0.0925	0.1670	0.2400	0.1644	0.1870
135	0.1050	0.0900	0.1680	0.2500	0.1626	0.1830
136	0.1050	0.0900	0.1600	0.2500	0.1558	0.1775
137	0.1050	0.0875	0.1450	0.2433	0.1549	0.1733
138	0.1050	0.0850	0.1325	0.2270	0.1553	0.1713
139	0.1000	0.0825	0.1200	0.1790	0.1526	0.1700
140	0.0950	0.0825	0.1160	0.1505	0.1435	0.1690
141	0.0950	0.0825	0.1140	0.1310	0.1440	0.1713
142	0.0950	0.0825	0.1095	0.1230	0.1430	0.1728
143	0.0950	0.0813	0.1125	0.1150	0.1427	0.1725
144	0.0950	0.0813	0.1050	0.1145	0.1484	0.1765
145	0.0950	0.0800	0.1000	0.1240	0.1518	0.1845
146	0.0975	0.0800	0.1030	0.1250	0.1530	0.1920
147	0.0975	0.0775	0.1050	0.1363	0.1531	0.2000
148	0.0950	0.0775	0.1180	0.1440	0.1527	0.2160
149	0.0963	0.0775	0.1310	0.1500	0.1571	0.2255
150	0.0988	0.0775	0.1340	0.1530	0.1513	0.2270
151	0.1025	0.0800	0.1190	0.1495	0.1485	0.2220
152	0.1025	0.0800	0.1095	0.1450	0.1459	0.2200
153	0.1025	0.0800	0.1000	0.1394	0.1499	0.2181
154	0.1013	0.0800	0.1000	0.1300	0.1531	0.2130
155	0.1013	0.0800	0.1000	0.1238	0.1480	0.2025
156	0.0925	0.0800	0.1000	0.1200	0.1454	0.1975
157	0.0925	0.0750	0.1000	0.1240	0.1424	0.1915
158	0.0925	0.0750	0.1000	0.1250	0.1406	0.1860
159	0.0950	0.0750	0.1000	0.1250	0.1402	0.1838
160	0.0950	0.0775	0.1075	0.1250	0.1441	0.1805
161	0.0950	0.0775	0.1220	0.1250	0.1416	0.1800
162	0.0950	0.0788	0.1250	0.1250	0.1474	0.1835
163	0.0925	0.0788	0.1280	0.1285	0.1523	0.1825
164	0.0938	0.0813	0.1308	0.1330	0.1459	0.1850
165	0.0950	0.0800	0.1213	0.1375	0.1463	0.1850
166	0.0950	0.0800	0.1130	0.1375	0.1493	0.1835
167	0.0950	0.0875	0.1085	0.1230	0.1509	0.1770
168	0.0925	0.0825	0.1100	0.1125	0.1565	0.1748
169	0.0925	0.0800	0.1100	0.1125	0.1566	0.1725
170	0.0925	0.0800	0.1050	0.1125	0.1477	0.1710
171	0.0925	0.0725	0.1085	0.1110	0.1525	0.1700
172	0.0913	0.0738	0.1155	0.1100	0.1598	0.1700
173	0.0900	0.0738	0.1225	0.1150	0.1675	0.1700
174	0.0900	0.0750	0.1320	0.1230	0.1744	0.1743
175	0.0913	0.0763	0.1535	0.1440	0.1791	0.1750
176	0.0913	0.0825	0.1583	0.1550	0.1762	0.1758
177	0.0938	0.0825	0.1590	0.1550	0.1750	0.1775
178	0.1000	0.0850	0.1500	0.1500	0.1786	0.1790
179	0.1025	0.0900	0.1500	0.1500	0.1793	0.1788
180	0.1038	0.0925	0.1495	0.1460	0.1897	0.1808
181	0.1088	0.0938	0.1475	0.1450	0.1977	0.1940

Week#	Pet Grade Chicken Fat	Feed Grade Chicken Fat	Tallow (Chicago)	Lard (Chicago)	Soybean Oil (Decatur)	Corn Oil (Decatur)
182	0.1088	0.0938	0.1469	0.1450	0.1944	0.2028
183	0.1088	0.0950	0.1428	0.1450	0.2009	0.2128
184	0.1113	0.0950	0.1370	0.1490	0.2010	0.2150
185	0.1113	0.0950	0.1395	0.1500	0.2093	0.2200
186	0.1113	0.0950	0.1420	0.1500	0.2099	0.2175
187	0.1125	0.0950	0.1400	0.1513	0.2070	0.2175
188	0.1125	0.0950	0.1400	0.1550	0.2064	0.2110
189	0.1138	0.0975	0.1440	0.1540	0.2047	0.2140
190	0.1163	0.0975	0.1450	0.1513	0.2004	0.2150
191	0.1138	0.0975	0.1400	0.1498	0.2014	0.2160
192	0.1138	0.0975	0.1320	0.1475	0.1985	0.2175
193	0.1150	0.0975	0.1340	0.1433	0.1971	0.2200
194	0.1138	0.0975	0.1400	0.1425	0.2077	0.2225
195	0.1138	0.0975	0.1460	0.1435	0.2161	0.2295
196	0.1125	0.1000	0.1535	0.1475	0.2267	0.2430
197	0.1163	0.1025	0.1600	0.1525	0.2297	0.2610
198	0.1213	0.1075	0.1550	0.1585	0.2304	0.2710
199	0.1238	0.1138	0.1600	0.1685	0.2300	0.2775
200	0.1300	0.1163	0.1663	0.1750	0.2329	0.2800
201	0.1313	0.1213	0.1735	0.1750	0.2273	0.2800
202	0.1425	0.1300	0.1820	0.1850	0.2272	0.2810
203	0.1475	0.1300	0.1850	0.1930	0.2256	0.2850
204	0.1475	0.1375	0.1850	0.1950	0.2218	0.2850
205	0.1475	0.1300	0.1825	0.1950	0.2197	0.2875
206	0.1500	0.1300	0.1785	0.1920	0.2167	0.2950
207	0.1425	0.1300	0.1681	0.1825	0.2105	0.2947
208	0.1425	0.1300	0.1635	0.1825	0.2146	0.2938
209	0.1425	0.1300	0.1590	0.1795	0.2140	0.2903
210	0.1450	0.1300	0.1510	0.1750	0.2109	0.2900
211	0.1400	0.1300	0.1525	0.1663	0.2089	0.2900
212	0.1400	0.1300	0.1590	0.1700	0.2116	0.2875
213	0.1425	0.1300	0.1693	0.1700	0.2123	0.2840
214	0.1450	0.1400	0.1710	0.1720	0.2112	0.2768
215	0.1488	0.1400	0.1645	0.1725	0.2147	0.2708
216	0.1488	0.1350	0.1625	0.1650	0.2198	0.2680
217	0.1488	0.1325	0.1630	0.1650	0.2187	0.2680
218	0.1400	0.1325	0.1643	0.1643	0.2258	0.2730
219	0.1400	0.1300	0.1710	0.1680	0.2267	0.2738
220	0.1375	0.1275	0.1688	0.1700	0.2230	0.2741
221	0.1325	0.1200	0.1605	0.1670	0.2216	0.2800
222	0.1300	0.1150	0.1555	0.1650	0.2230	0.2850
223	0.1275	0.1125	0.1533	0.1650	0.2300	0.2863
224	0.1263	0.1125	0.1640	0.1670	0.2402	0.2950
225	0.1250	0.1125	0.1750	0.1788	0.2341	0.2950
226	0.1300	0.1125	0.1850	0.1860	0.2272	0.2963
227	0.1400	0.1213	0.1850	0.1950	0.2290	0.2995

Sources for these price series include the Commodity Research Bureau, Jacobsen Market Report and USDA-AMS.

Table A26. Summary of Monthly Methanol, Ethanol and Glycerine Prices.

	Average Prices		
	Ethanol(gal)	Methanol(gal)	Glycerin (lb)
2001	$1.51	$0.63	$0.71
2002	$1.44	$0.47	$0.64
2003	$1.21	$0.75	$1.02
All Months	$1.39	$0.61	$0.77

Notes: Prices for ethanol, methanol, and glycerine were collected from the Chemical Market Reporter (http://chemicalmarketreporter.com), a weekly chemical trade magazine. Reported prices are based on information received from suppliers and as such can be used as an estimate of market prices, but they are not necessarily prices at which transactions have occurred. Furthermore, many of these chemicals would be purchased under long term contracts. The price series were collected from January 2001 through November 2003 pending availability and consistency in the price series. Glycerin is an important by-product of biodiesel production. Prices shown are for a bulk truckload delivered in $/lb. Prices ranged from $0.60 to $1.23/lb. Methanol is used in all methyl ester production. Prices shown are spot prices for a barge-load, free on board at the producing point (Gulf Coast) in $/gallon. Prices ranged from $0.335 to $0.955/gal. Ethanol can also be used to produce biodiesel. Prices shown are for fuel grade tanks, free on board in $/gallon. Prices ranged from $1.16 to $1.59/gallon. Ethanol was not used in this analysis but is referred to here because ethyl esters can also meet the criteria for biodiesel. However, it generally is more costly compared to methanol.