Biodiesel from Fuel Crops in Hawaii

Report to the Environmental Protection Agency (EPA)

May 29, 2009

CLEAN FUELS FOR CLEAN AIR
Clean Cities
Honolulu

Oceanic Institute
An Affiliate of Hawai'i Pacific University

PACIFIC BIODIESEL
TECHNOLOGIES

GP
GracePacific
CORPORATION

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I. Overview

With 93% of its energy coming from fossil fuels and almost no local energy production resources of its own, Hawaii is the single most petroleum-dependent state in the nation. Hawaii's dependency on imported energy leaves the state extremely vulnerable to price and availability fluctuations, resulting in decreased energy security.

One of the ways that Hawaii has been working to gain greater self-reliance is through the production and use of biodiesel. There are several advantages to using biodiesel and biodiesel blends that contribute to its growing popularity: lower toxicity of biodiesel compared to petroleum diesel and lower emissions of carbon monoxide, SOx and particulates; greater lubricity, which reduces wear on engines; similar in cost to petroleum diesel; carbon neutral emissions – it does not increase carbon dioxide (a greenhouse gas) in the atmosphere and it helps reduce our dependence on foreign oil and stimulates local economy and promotes local agriculture.

However, biodiesel production in the state currently relies solely upon waste cooking oil for feedstock and has a total production capacity of approximately 1.2 million gallons per year. When compared to the estimated 50 million gallons of petroleum diesel that are consumed in Hawaii (2006), one can see that there is a great deal of potential for expansion of this resource. While waste-derived biodiesel has provided an important opportunity to convert a large portion of otherwise land-filled waste into a valuable energy source, the recent boom in biodiesel interest has resulted in a much larger demand than can be satisfied by this feedstock source alone.

A project for Honolulu Clean Cities (HCC) "Biodiesel from Fuel Crops in Hawaii", funded by the Environmental Protection Agency (EPA), explored and evaluated a number of crop materials currently grown in Hawaii to determine their suitability as feedstock for making an American Society for Testing and Materials (ASTM) grade biodiesel. The purpose of this project was to develop an understanding of the quality and yield of biodiesel produced from a variety of different island feedstock sources and measure the emissions generated.

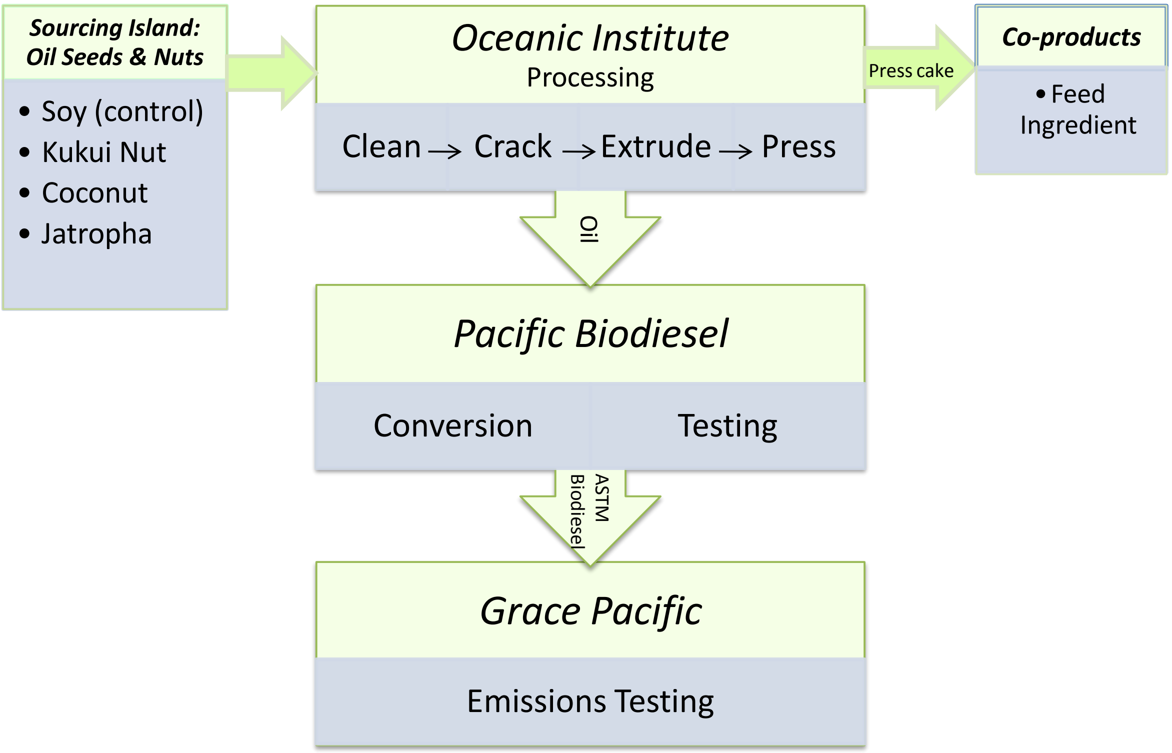
As well as energy, Hawaii is also largely dependent on food from the mainland and overseas. The state’s livestock industries are rapidly disappearing, with the cost of importing animal feed a major contributor to the decline. The project also looked at the potential economic value of using the co-products as animal feed ingredients, to help reduce the feeding costs for Hawaii’s farmers.

Overview

The HCC members: Oceanic Institute (OI), Pacific Biodiesel Technologies (PBT) and Grace Pacific Corporation (GPC) partnered together to undertake this project.

Honolulu Clean Cities

EPA Emission Reduction Grant



Sourcing Island: Oil Seeds & Nuts

- Soy (control)
- Kukui Nut
- Coconut
- Jatropha

Oceanic Institute

Processing

Clean → Crack → Extrude → Press

Press cake

Co-products

- Feed Ingredient

Oil

Pacific Biodiesel

Conversion

Testing

ASTM Biodiesel

Grace Pacific

Emissions Testing

II. Oceanic Institute – Seed and Nut Processing & Analysis

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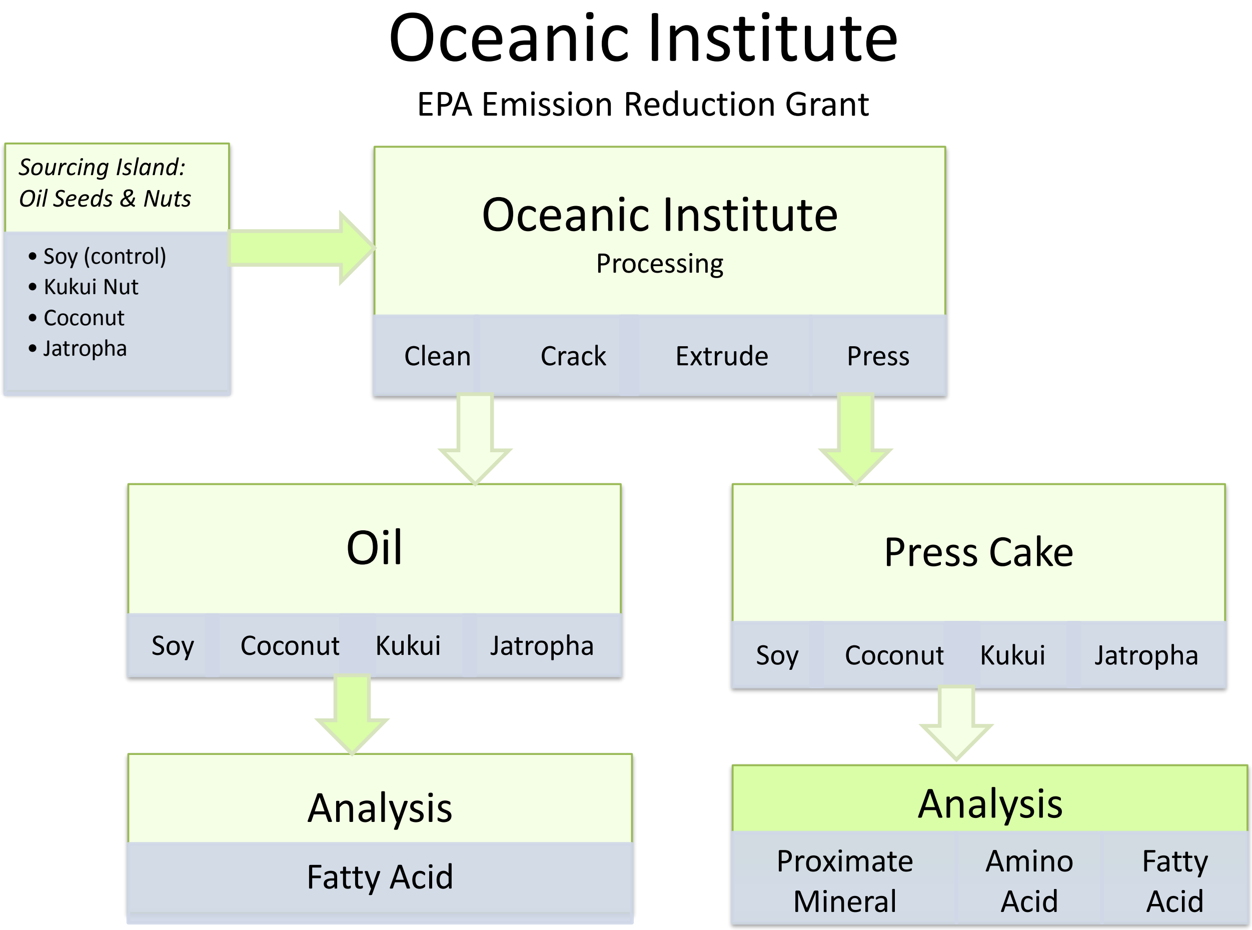
Abstract

Oceanic Institute (OI)'s feed processing complex was tasked with the extraction of oil from coconut, kukui nut and jatropha seeds. Whole soybeans were also processed and extracted as a control oil seed. Oil content of oil seeds and nuts ranged from 18-58%. OI's analytical lab characterized the crude oil extracted and the presscake co-products generated from the oil extraction process. Fatty acid profiles of the crude oil and presscake were determined for each feedstock. The presscakes were also characterized for use as an animal feed by determining their crude protein content, which ranged from 7- 46%, crude fat from 6-10%, ash from 2-6%, moisture 8-9.5%, and crude fiber content that ranged from 7-76%. Additional analysis of the protein quality was determined by amino acid content. Yields of oils from extracted feed stock material were from 10-33%, electrical consumption per kg of crude oil extracted ranged from 1.1 - 4.5 kWh. All extracted oils; soy, coconut, kukui, and jatropha were filtered and delivered to Pacific Biodiesel for conversion into ASTM biodiesel.



Materials & Method

Test materials of whole soy beans (2,000 kgs) were shipped to the Oceanic Institute's processing facility from Insta-Pro, Des Moines, Iowa, coconuts (100 kg) and kukui nuts (100 kg) were shipped in from the island of Molokai by Hawaiian Steam Inc., and jatropha seeds (100 kg) were shipped in from the Philippines by Pacific Biodiesel Technologies.

The coconut, kukui nuts and jatropha seeds were preprocessed at OI feed processing laboratory by cracking and removing the shells, sun drying, particle size reduction, and through addition and mixing of shell/fiber to the coconut, and kukui pulp to assist with mechanical oil pressing. This was necessary for the soft oily pulp to pass through the oil press. Fiber or shell needed to be added to be able to press the oil out of the pulp in order to maximize oil recovery and minimizing non-lipid particulate contamination of the crude oil.

Particle size reduction of the nut pulp to approximately gravel size (< 2mm) was accomplished by a 1 horsepower Hobart Food Chopper Model 84181D for softer nut meat materials (coconut and kukui) and by a 3 horsepower Hammermill for harder and fibrous materials such as shells. Mixing was accomplished in batches ranging from 40-80 kg in a Davis (HC Davis & Sons Mill Machinery Co.) Double Ribbon Blender, for 15 minutes, which is verified under these specifications to produce a statistically homogenous mix.

Oil extraction was achieved using a 15 horsepower continuous horizontal Insta-Pro Model 750 oil press. By controlling the temperature, fiber content of raw materials, particle size, feed rates, and presscake thicknesses, the load on the oil press was thereby controlled to recover reasonably uncontaminated crude oils, recovering most of the crude oil originally in the raw oilseed. The coproduct presscakes should be able to be rendered to less than 10% crude fat.

Hot pressing involved using a 50 horsepower Insta-Pro 600 Jr. extruder, immediately prior to oil pressing, using a standard auger configuration for producing full fat soy. The extrusion process produces a rapid, high shear, high heat, and high pressure environment in the extruder barrel, rupturing the oil cells and releasing the oil from seeds. Some general and desirable results in the case of oil pressing are the compression of the ruptured oil cells and the release of lipids otherwise tightly bound in the raw material. Cold pressing is preferable from an energy standpoint since extruders are typically high energy consumers. In some cases cold pressing was adequate as some of the materials readily released lipids without extrusion.

Pressing methods for soybeans were already well established, whereas efficient methods needed to be determined for the coconut, kukui nut, and jatropha. General machine operating procedures and empirical observations of oil clarity as well as estimated oil content in the presscake were used as guidelines for obtaining clean and efficient oil pressings, which were later verified against chemical analysis of the raw materials, expelled oil, and presscakes. Lastly, the crude oils and presscake coproducts were further analyzed from both the standpoint of biofuel and feed production.

Soybean Processing

Dry whole raw soybeans were procured for use as a standard control material for the oil extraction process. Industry standards for soybean extrusion and oil extraction developed by Insta-Pro were utilized. Soybeans were first extruded and then pressed to extract the oil; running the presscake back through the oil press increased the oil yeilds. An Insta-Pro 600 Jr. Extruder was run in line with the Insta-Pro 750 Oil Press. Soybeans entered the extruder whole or ground, producing full fat soy, which in turn was fed hot into the oil press, which squeezed out the oil.

Coconut Processing

Coconuts delivered were husked but not shelled, the shell was largely intact and clean. The shells were cracked and split, drained, and allowed to sun dry, whereupon the coconut meat (copra) was separated from the shell. Separately, the copra and shells were reduced to gravel size pieces by means of a Hobart Food Chopper and Hammermill respectively. A dry mixture of 60% copra to 40% shell by weight was batched, mixed, and cold pressed. The batched mixture was fed directly into the oil press at room temperature.

Kukui Nut Processing

Kukui nuts were husked but not shelled. The nuts were received with shell largely intact and clean. The nuts were hand cracked, and the nut meat was separated from the shell, the shell accounted for 75% of the total nut weight while oil bearing nut meat made up the remaining 25%. Separately, the nut meat and shells were then reduced to gravel size pieces by means of a Hobart Food Chopper and Hammermill respectively. A dry mixture of 75% kukui nut meat to 25% shell by weight was batched, mixed, and cold pressed, the batched mixture was fed directly into the oil press at room temperature.

Jatropha Seed Processing

Jatropha seeds where husked, but a thin shell remained around the seed which were largely intact and clean. The seeds were reduced to gravel size pieces by means of a Hammermill and cold pressed. Ground seed and husks were fed directly into the oil press at room temperature. In order to reduce the oil content of the presscake, jatropha was cold pressed three (3) times.

Results

Soybean results*:* Table 1. The whole soybeans were extruded hot and the hot oil was extracted from one pass through the oil press. The raw soybeans were reduced in oil content from the original crude fat levels of 18.00% to 7.40% that remained in the final presscake. An oil yield measured by weight recovery was 10.04%, from the original raw material. The process of hot extrusion and hot oil pressing consumed 4.51 kilowatt hours per kilogram of crude soy oil produced. A total of 22 kgs of crude soy oil was produced and delivered to Pacific Biodiesel.

Table 1

Process	Data			
Raw Whole Soybean Crude Fat	18.00	±	0.00	%
Soybean Presscake Crude Fat	7.40	±	0.07	%
Soybean Oil Yield (by weight)	10.04			% Oil to raw material
Soybean Processing Efficiency	4.51			kWh **/** kg Oil

Coconut results: Table 2. The coconut meat and shell mix were processed through a single pass through the cold oil press reducing the lipid levels from 57.75% to 8.92% in the presscake, the hot extrusion process was not required. An oil yield measured by weight recovery was 27.39%, from the original raw material. The oil pressing process consumed 1.14 kilowatt hours per kilogram of crude coconut oil produced. A total of 16.5 kgs of crude coconut oil was produced and delivered to Pacific Biodiesel.

Table 2.

Process	Data			
Raw Coconut Copra Crude Fat	57.75	±	0.00	%
Coconut Presscake Crude Fat	8.92	±	0.01	%
Coconut Yield (by weight)	27.39			% Oil to raw material
Coconut Processing Efficiency	1.14			kWh **/** kg Oil

Kukui Nut results: Table 3. The kukui meat and shell mix were processed through a single pass through the cold oil press reducing lipid levels from 57.05% to 6.59% in the presscake, the hot extrusion process was not required. An oil yield measured by weight recovery was 12.39%, from the original raw material. The oil pressing process consumed 2.65 kilowatt hours per kilogram of crude kukui nut oil produced. A total of 11.75 kgs of crude kukui nut oil was produced and delivered to Pacific Biodiesel.

Table 3.

Process	Data			
Raw Kukui nut Crude Fat	57.05	±	0.07	%
Kukui Presscake Crude Fat	6.59	±	0.34	%
Kukui Oil Yield (by weight)	12.08			% Oil to raw material
Kukui nut Processing Efficiency	2.65			kWh / kg Oil

Jatropha Seed results*:* Table 4. The jatropha seeds with shell were processed 3X through the oil press pressing process to reduce the lipid levels from 46.87% to 9.91% in the presscake. Oil yields by weight recovery of 32.75% crude oil from the original raw material. and consuming 1.20 kilowatt hours per kilogram of crude jatropha oil. A total of 13.10 kgs of crude jatropha oil was delivered to Pacific Biodiesel.

Table 4.

Process	**Data**			
Raw Jatropha Crude Fat	46.87	±	0.02	%
Jatropha Presscake Crude Fat	9.91	±	0.43	%
Jatropha Yield (by weight)	32.75			% Oil to raw material
Jatropha Processing Efficiency	1.20			kWh **/** kg Oil

In summary of the processing yields of oils from extracted feed stock material at OI were from 10-33%. The electrical consumption per kg of crude oil extracted ranged from 1.1 - 4.5 kWh. All extracted oils collected soy, coconut, kukui and jatropha, were filtered and sealed in 5-gal plastic containers and delivered to Pacific Biodiesel for conversion into biodiesel.

Post-press Oil and Press Cake Analysis

The products and co-products generated from the processing of the oil nuts and seeds feed stocks were the crude oils and the presscakes. These crude oils and presscakes were analyzed for their fatty acid composition (Tables 5 & 6). As expected the crude oils and their presscake co-products were similar in fatty acid composition. The essential fatty acids required in aquaculture fish and shrimp nutrition are the five fatty acids highlighted in bold in Table 5 & 6. These fatty acids are linolenic (C18:2n-6), linolenic (C18:3n-3), arachidonic (C20:4n-6), EPA (C20:5n-3) and DHA (C22:6n-3). However only two of the essential five essential fatty acids are found in the oils and the presscakes, linolenic (C18:2n-6) and linolenic (C18:3n-3), exceptions are linolenic is missing in the coconut and jatropha oil and presscake.

Table 5. Fatty Acid Profiles of Crude Oils

Fatty Acid		**Soy oil** %	**Coconut oil** %	**Kukui Nut oil** %	**Jatropha oil** %
Octanoic (Caprylic)	C8:0	0.00	5.50	0.00	0.00
Decanoic (Capric)	C10:0	0.00	6.58	0.00	0.00
Dodecanoic (Lauric)	C12:0	0.00	57.47	0.00	0.00
Tetradecanoic (Myristic)	C14:0	0.00	17.64	0.00	0.00
Hexadecanoic (Palmitic)	C16:0	10.72	3.91	5.24	12.54
Hexadecenoic (Palmitoleic)	C16:1n-7	0.00	0.00	0.00	0.00
Hexadecadienoic	C16:2n-4	0.00	0.00	0.00	0.00
Hexadecatrienoic	C16:3n-4	0.00	0.00	0.00	0.00
Octadecanoic (Stearic)	C18:0	5.24	1.35	2.40	7.24
Octadecenoic (Oleic)	C18:1n-9	23.02	4.10	17.44	48.08
Octadecenoic (Oleic)	C18:1n-7	0.00	0.00	0.00	0.52
Octadecadienoic (Linoleic)	**C18:2n-6**	**53.18**	**3.45**	**46.76**	**31.62**
Octadecatrienoic (Linolenic)	**C18:3n-3**	**7.84**	**0.00**	**28.16**	**0.00**
Octadecatetraenoic (Stearidonic)	C18:4n-3	0.00	0.00	0.00	0.00
Eicosanoic (Arachidic)	C20:0	0.00	0.00	0.00	0.00
Eicosenoic (Gadoleic)	C20:1n-9	0.00	0.00	0.00	0.00
Eicosatetraenoic (Arachidonic)	**C20:4n-6**	**0.00**	**0.00**	**0.00**	**0.00**
Eicosatetraenoic	C20:4n-3	0.00	0.00	0.00	0.00
Eicosapentanoic (EPA)	**C20:5n-3**	**0.00**	**0.00**	**0.00**	**0.00**
Docosenoic (Erucic)	C22:1	0.00	0.00	0.00	0.00
Docosapentanoic (DPA)	C22:5n-3	0.00	0.00	0.00	0.00
Docosahexanoic (DHA)	**C22:6n-3**	**0.00**	**0.00**	**0.00**	**0.00**
Identified % Total Fatty Acids:		100.00	100.00	100.00	100.00
Unidentified % Total Fatty Acid:		0.00	0.00	0.00	0.00
%Fatty Acid Total:		100.00	100.00	100.00	100.00

Table 6. Fatty Acid Profiles of Coproduct Presscakes

Fatty Acid		**Soybean cold press 1** %	**Coconut cold press 1** %	**Kukui cold press 1** %	**Jatropha cold press 3** %
Octanoic (Caprylic)	C8:0	0.00	5.71	0.00	0.00
Decanoic (Capric)	C10:0	0.00	7.04	0.00	0.00
Dodecanoic (Lauric)	C12:0	0.00	61.24	0.00	0.00
Tetradecanoic (Myristic)	C14:0	0.00	18.10	0.00	0.00
Hexadecanoic (Palmitic)	C16:0	12.06	3.28	5.05	14.84
Hexadecenoic (Palmitoleic)	C16:1n-7	0.00	0.00	0.00	0.72
Hexadecadienoic	C16:2n-4	0.00	0.00	0.00	0.00
Hexadecatrienoic	C16:3n-4	0.00	0.00	0.00	0.00
Octadecanoic (Stearic)	C18:0	5.14	1.09	2.10	6.76
Octadecenoic (Oleic)	C18:1n-9	22.35	2.67	17.87	46.81
Octadecenoic (Oleic)	C18:1n-7	1.00	0.00	0.00	0.67
Octadecadienoic (Linoleic)	**C18:2n-6**	**51.91**	**0.87**	**47.38**	**30.21**
Octadecatrienoic (Linolenic)	**C18:3n-3**	**7.54**	**0.00**	**27.60**	**0.00**
Octadecatetraenoic (Stearidonic)	C18:4n-3	0.00	0.00	0.00	0.00
Eicosanoic (Arachidic)	C20:0	0.00	0.00	0.00	0.00
Eicosenoic (Gadoleic)	C20:1n-9	0.00	0.00	0.00	0.00
Eicosatetraenoic (Arachidonic)	**C20:4n-6**	**0.00**	**0.00**	**0.00**	**0.00**
Eicosatetraenoic	C20:4n-3	0.00	0.00	0.00	0.00
Eicosapentanoic (EPA)	**C20:5n-3**	**0.00**	**0.00**	**0.00**	**0.00**
Docosenoic (Erucic)	C22:1	0.00	0.00	0.00	0.00
Docosapentanoic (DPA)	C22:5n-3	0.00	0.00	0.00	0.00
Docosahexanoic (DHA)	**C22:6n-3**	**0.00**	**0.00**	**0.00**	**0.00**
Identified % Total Fatty Acids:		100.00	100.00	100.00	100.00
Unidentified % Total Fatty Acid:		0.00	0.00	0.00	0.00
%Fatty Acid Total:		100.00	100.00	100.00	100.00

In addition to the fatty acid profiles, the presscakes were also characterized for use as animal feed by proximate and mineral analysis (Table 7). Crude protein content and crude fiber values ranged widely from 7- 46% and 7-76% respectively. Crude fat values ranged from 6-10%, ash from 2-6%, and moisture 8-9.5%, which were not as variable.

Table 7. Coproduct presscake proximate and mineral analysis

Analysis	**Soybean presscake**	**Coconut presscake**	**Kukui presscake**	**Jatropha presscake**
Proximate	92.03	90.46	90.24	90.85
Ash (%)	5.12	2.04	3.94	5.78
Crude Protein (%)	46.36	7.34	7.48	19.93
Crude Fat (%)	7.97	6.30	10.13	9.48
Crude Fiber (%)	6.58	45.67	62.66	36.07
	0.63	0.16	0.19	0.63
Potassium (%)	2.13	0.86	0.33	1.41
Calcium (%)	0.25	0.03	1.79	0.54
Magnesium (%)	0.31	0.12	0.41	0.51
Sodium (%)	0.02	0.08	0.05	0.06
Boron (ppm)	31	5	9	22
Copper (ppm)	20	8	5	21
Iron (ppm)	51	44	56	84
Manganese (ppm)	34	178	53	490
Zinc (ppm)	45	14	12	77

Additional analysis of the protein quality of the co-product presscake was also determined by its amino acid (AA) content shown in Table 8. Since soy protein is a fairly good vegetable protein source of amino acids it can be used as a standard with the exception of the AA methionine, which is low. Using the soy protein essential AA profile as a standard demonstrates that the essential AA found in jatropha presscake is about half or lower than what is found in soybeans presscake. The essential AA found in the coconut and kukui nut presscakes were even lower than the jatropha presscake. Methionine levels in the presscake for soy, kukui nut, coconut and jatropha were .41,>.15,>.04, >.00 respectively. Quality of protein of Hawaii nuts and oilseed compared to soy presscake is fairly poor.

Table 8: Presscake Amino acid (AA) contents: g /100g sample

Sample No.	AA	**Soybean presscake** g /100g	**Coconut presscake** g /100g	**Kukui presscake** g /100g	**Jatropha presscake** g /100g
Non-essential AA					
1	Ala	3.60	0.34	0.41	2.00
2	Asp+ASN	1.40	0.25	0.80	0.69
4	Cys	0.55	0.00	0.04	0.72
6	Glu+Gln	4.72	0.92	0.96	2.17
7	Gly	2.93	0.36	0.60	2.11
8	Pro	3.38	0.33	0.02	1.77
9	Ser	2.61	0.31	0.25	1.39
10	Tyr	2.02	0.49	0.21	0.58
	Taurine	0.00	0.00	0.00	0.00
Essential AA					
1	Arg	7.25	1.26	0.84	5.55
2	His	1.34	0.02	0.13	0.79
3	Ile	1.98	0.22	0.31	0.99
4	Leu	2.64	0.38	0.50	1.24
5	Lys	1.81	0.22	0.48	0.37
6	Met	0.41	0.04	0.15	0.00
7	Phe	1.94	0.43	0.31	1.10
8	Thr	2.79	0.48	0.72	2.44
9	Trp	0.03	0.07	0.02	0.28
10	Val	1.59	0.25	0.30	1.73
Subtotal of No Essential AA		21.21	3.00	3.29	11.44
Subtotal of Essential AA		21.79	3.37	3.77	14.49
Total		43.00	6.37	7.06	25.93

Summary of Processing

Processing was tailored to suit the oil pressing requirements for each test ingredient. The 18% crude fat soybean meal was extruded and hot pressed and a little over half the oil was pressed out. The high 57% plus crude fat of the kukui nut and coconut meats, when mixed with ground-up shell was cold pressed in one pass and reduced the oil yields to 12% and 27% respectively. The high 47% crude fat content of jatropha seeds with hulls was cold pressed three (3) times to reduce the press cake oil content to less than 10%. Overall results below show that the crude oil content of each presscake material was reduced to less than 10%. The ratio of oil to raw material yield and the electrical consumption of each process per unit of crude oil were obtained.

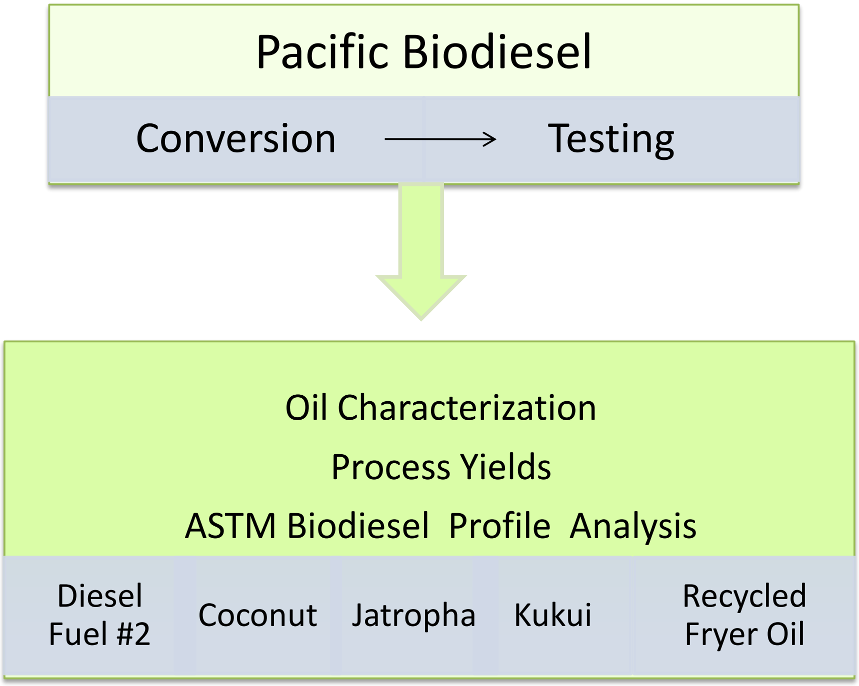
Test Process	Crude Fat of Oilseed %EE	Crude Fat of Presscake %EE	Oil to raw material %	Electrical Consumption kWh / kg Oil
Soybean Seeds	18.00 ± 0.00	7.40 ± 0.07	10.04	4.51
Kukui Nuts	57.05 ± 0.07	6.59 ± 0.34	12.08	2.65
Coconuts	57.75 ± 0.00	8.92 ± 0.01	27.39	1.14
Jatropha Seeds	46.87 ± 0.02	9.91 ± 0.43	32.75	1.20

Conclusions

The project showed that island nuts and oilseeds can be processed into oils for conversion into biodiesel fuel and there are uses for the presscake probably as a ruminant (cattle) feed. However the quantities (100kg) of coconut, kukui nut and jatropha seeds that were sourced and processed in the above project were not enough feedstock material to get a sustained processing run for accurate data acquisition. The oil press production rate was 250 kg of feedstock / hr. With only a 100kg of feedstock it was impossible to optimize a single oil extraction run per feedstock. More feedstock material would have provided replicated runs, and optimizing oil extraction could have been run. An estimate of a ton more of product was needed to get accurate readings for these various feedstocks. To become an economic reality there is still a long way to go before the use of locally grown oilseed and nuts can be pressed into oil for the conversion of biodiesel fuels.

Pacific Biodiesel

EPA Emission Reduction Grant



Pacific Biodiesel

Conversion → Testing

Oil Characterization

Process Yields

ASTM Biodiesel Profile Analysis

Diesel Fuel #2

Coconut

Jatropha

Kukui

Recycled Fryer Oil

III. Pacific Biodiesel Technologies – Oil Characterization, Biodiesel Processing & Analysis

Lee Litvin—Pacific Biodiesel Technologies

Abstract

Three raw oils (coconut, kukui, and jatropha) were successfully processed into methyl esters using a process developed by Pacific Biodiesel Technologies. The coconut methyl ester was the only sample to pass the ASTM D6751 specification for biodiesel quality. The jatropha methyl ester had a high sulfur content. The kukui methyl ester had a high carbon residue value and a low cetane number. Analysis of the raw oils included tests for water content, moisture and volatile content, insoluble impurities content, unsaponifiable matter content, sulfur content, phosphorus content, free fatty acid content, and fatty acid profile. The jatropha oil had a very high sulfur content of 243.77ppm. The kukui oil had a very high free fatty acid content of 27.8%. There were processing difficulties with the raw jatropha and raw kukui oils. Both of these oils had a very high insoluble impurities (sediment) component that had to be settled and separated before the oil could be processed. The kukui oil also required a water degumming step to help the ester-glycerin phase separation during production. Process yields varied between the samples. The coconut oil had the highest conversion yield to methyl ester with a range of 90 – 92%. Jatropha oil had a conversion yield of 89 – 91%. Kukui had a conversion yield of 84 – 89%.

Oil Characterization

The three oils, coconut, kukui, and jatropha were harvested directly from a press. No additional processing steps were taken to clean the oil. We received two, two-gallon buckets of coconut and jatropha oils and one, two-gallon bucket of kukui oil. The buckets were each homogenized separately and samples of each oil were taken. The analyses performed and corresponding results for each of the oil samples are listed in Table 1.

Table 1: Oil Characterization

Test			Units	Coconut Oil	Kukui Oil	Jatropha Oil
Water by Karl Fischer			ppm	1673	2461	1808
Moisture & Volatile			% mass	0.38	0.42	0.22
Insoluble Impurities			% mass	0.32	0.96	0.97
Unsaponifiable Matter			% mass	0.47	0.34	0.50
MIU Total			% mass	1.17	1.72	1.69
Sulfur			ppm	10.67	37.09	243.77
Phosphorus			ppm	35.5	75.1	12.4
Free Fatty Acid			% mass*	2.44	27.8	3.96
Fatty Acid Profile						
	C8:0	Caprylic	%	6.02	0.07	
	C10:0	Capric	%	5.83	0.07	
	C12:0	Lauric	%	44.88	0.55	
	C12:1	Dodecenoic	%	0.05		
	C14:0	Myristic	%	15.40	0.23	0.06
	C16:0	Palmitic	%	8.68	6.11	14.20
	C16:1	Palmitoleic	%	0.20	0.05	0.78
	C17:0	Margaric	%			0.14
	C18:0	Stearic	%	2.78	2.76	7.29
	C18:1	Oleic	%	8.41	18.29	46.78
	C18:2	Linoleic	%	6.69	44.97	30.13
	C18:3	Linolenic	%	0.78	26.10	0.27
	C18:4	Octadecatetraenoic	%		0.11	
	C20:0	Arachidic	%	0.11	0.07	0.21
	C20:1	Gadoleic	%	0.07	0.54	0.08

*As Oleic Acid

The kukui and jatropha oils contained large amounts of insoluble impurities (solids), 0.96 and 0.97% respectively. When settled, the solids were muddy in texture and consistency and were not easily separated from the oil. This demonstrates the need for oil pretreatment. The solids must be removed. Oil characteristics which may necessitate additional oil or biodiesel processing are the high free fatty acid and phosphorus levels of kukui oil and the high sulfur content of jatropha oil.

Biodiesel Processing

Biodiesel was produced using proprietary technology from Pacific Biodiesel Technologies (PB Tech).

First Trials

Each sample was initially homogenized in its container. A representative sample was taken and processed using the process developed by PB Tech. The large amount of sediment in the kukui and jatropha samples proved to be a hindrance in the processing. A clean separation of ester and glycerin layers did not occur with either the kukui or jatropha. The coconut oil processed well. The sediment in the coconut oil did not pose any restrictions to the process.

Oil Settling

The kukui and jatropha oil samples were left to settle in their container. The "clean" oil was decanted off the top and processed. The jatropha oil processed well without the sediment contamination. No more process difficulties were found. The kukui oil continued to have difficulty separating. An emulsion effect was occurring.

Degumming

To combat the emulsion effect during processing, the kukui oil was treated using a water degumming technique. Water, 1% of oil mass, was added to oil that was heated to 70°C. The water and oil were thoroughly mixed for one hour and allowed to settle overnight. After settling, the separated water was removed from the oil. The oil was then processed into biodiesel without difficulty. The emulsion that occurred in the first trials did not occur after the oil was degummed.

Processing Results

All three oil samples, coconut, kukui, and jatropha produced biodiesel.

Process Yields (by volume)

- Coconut Ester: 90 – 92%
- Kukui Ester: 84 – 89%
- Jatropha Ester: 89 – 91%

ASTM D6751 Analysis

Table 2 displays a summary of the analysis of the three biodiesel samples. The full certificates of analyses of the samples are attached in the appendix. The coconut biodiesel sample passed all the specifications described in ASTM D6751. The kukui biodiesel sample failed the carbon residue test. The jatropha biodiesel sample failed the sulfur test.

Table 2: Biodiesel Analysis

Test	Method	Units	Limit	Coconut	Kukui	Jatropha
Ca and Mg, combined	EN 14538	ppm	5 max	<1.0	<2	<1.0
Na and K, combined	EN 14538	ppm	5 max	<1.0	<5	<1.0
Flash Point	D 93	°C	93	104	166	164
Water and Sediment	D 2709	% volume	0.050 max	<0.005	<0.005	<0.005
Kinematic Viscosity	D 445	mm^2/s	1.9 - 6.0	2.71	3.92	4.38
Sulfated Ash	D 874	% mass	0.020 max	0.004	0.011	<0.002
Sulfur	D 5453	ppm	15 max	0.61	5.9	*56.5*
Copper Strip Corrosion	D 130		3 max	1a	1a	1a
Cetane Number	D 613		47 min	47.5	*43.3*	51.3
Cloud Point	D 5773	°C	report	-5.0	-7.8	5.8
Carbon Residue	D 4530	% mass	0.050 max	0.025	*0.066*	0.021
Acid Number	D 664	mg KOH/g	0.50 max	0.221	0.370	0.194
Free Glycerin	D 6584	% mass	0.020 max	0.002	0.007	0.005
Total Glycerin	D 6584	% mass	0.240 max	0.052	0.175	0.187
Phorphorus content	D 4951	% mass	0.001 max	<0.00005	<0.00005	<0.00005
Distillation Temp.	D 1160	°C	360 max	347	355	352
Oxidation Stability	EN 14112	hours	3 min	4.7	3.1	3.05

Conclusion

Coconut Oil

The raw coconut oil sample that was processed by PB Tech was low in free fatty acid and contaminants. This allowed for little pretreatment and typical biodiesel processing parameters. The sample process by PB Tech passed the ASTM D6751 specification for biodiesel. The biodiesel has very good cold flow properties with a cloud point of -5.0°C, low viscosity, and a relatively high oxidation stability value. Production yields of coconut oil to coconut biodiesel ranged from 90 to 92% by volume. Overall, coconut oil is a fine feedstock for biodiesel production.

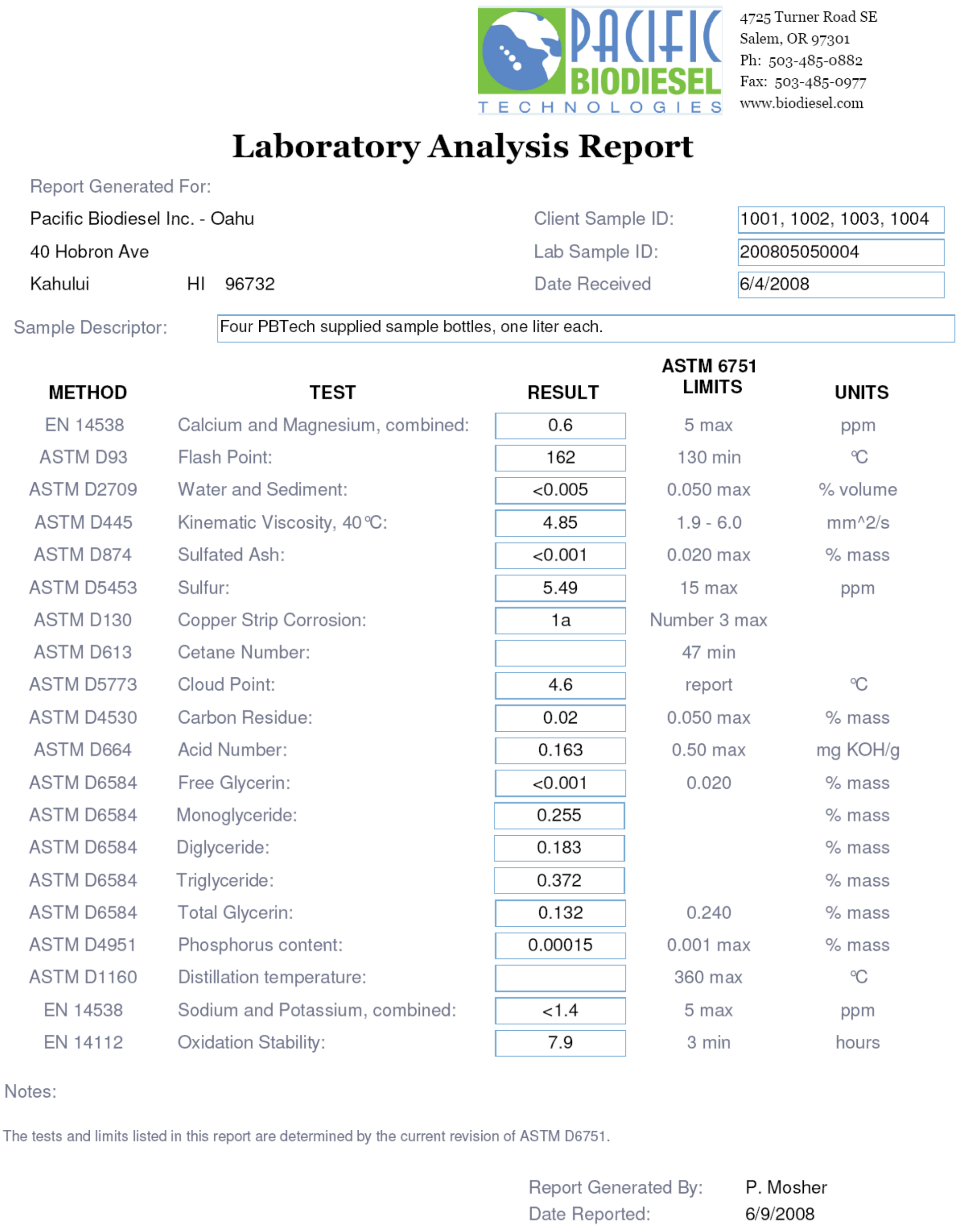
Kukui Oil

Raw kukui oil has qualities that make for difficult biodiesel production. First, there is high sediment content on the oil. This sediment can be gravity settled, but results in sediment with a consistency of a thick mud. It was difficult to determine how much oil was lost in the emulsion with the sediment. Once the sediment has been removed, there is some substance still remaining in the oil that causes emulsions during the biodiesel process. This substance or substances must be removed prior to biodiesel production. It was found that water degumming was an effective tool to remove the emulsifiers. After contaminating emulsifiers are removed from the oil, the oil must be further treated because of the high free fatty acid level (28%). Most industrial biodiesel production facilities today do not have the capability to handle a feedstock with an initial free fatty acid level over 15%. To produce biodiesel from this oil, additional process steps need to be taken. After additional process steps were taken by PB Tech, full conversion from kukui oil to kukui methyl ester was completed. Typical production yields of pretreated kukui oil ranged from 84 to 89% by volume.

The kukui methyl ester sample failed two parameters of ASTM D6751, cetane number and carbon residue. Therefore, it cannot be considered biodiesel.

Jatropha Oil

Before effectively converting the jatropha oil to biodiesel, large amount of sediment had to be settled out of solution. Only the decanted “clean” oil from the top was used for production. The most surprising aspect of the jatropha oil was its very high sulfur content (244 ppm). Using current processing parameters the sulfur content of the finished biodiesel was reduced to 56.5ppm. This value is above the ASTM limit for sulfur, 15ppm. Additional process steps must be taken to reduce the sulfur level of this fuel if it is to be used for on-road use in the United States. Such a process might include distillation. Production yields of jatropha oil to jatropha methyl ester ranged from 89 to 91% by volume. Other than the high sulfur content, jatropha oil would be a fine feedstock for biodiesel production.



PACIFIC BIODIESEL TECHNOLOGIES

4725 Turner Road SE
Salem, OR 97301
Ph: 503-485-0882
Fax: 503-485-0977
www.biodiesel.com

Laboratory Analysis Report

Report Generated For:

Pacific Biodiesel Inc. - Oahu
40 Hobron Ave
Kahului HI 96732

Client Sample ID: 1001, 1002, 1003, 1004
Lab Sample ID: 200805050004
Date Received 6/4/2008

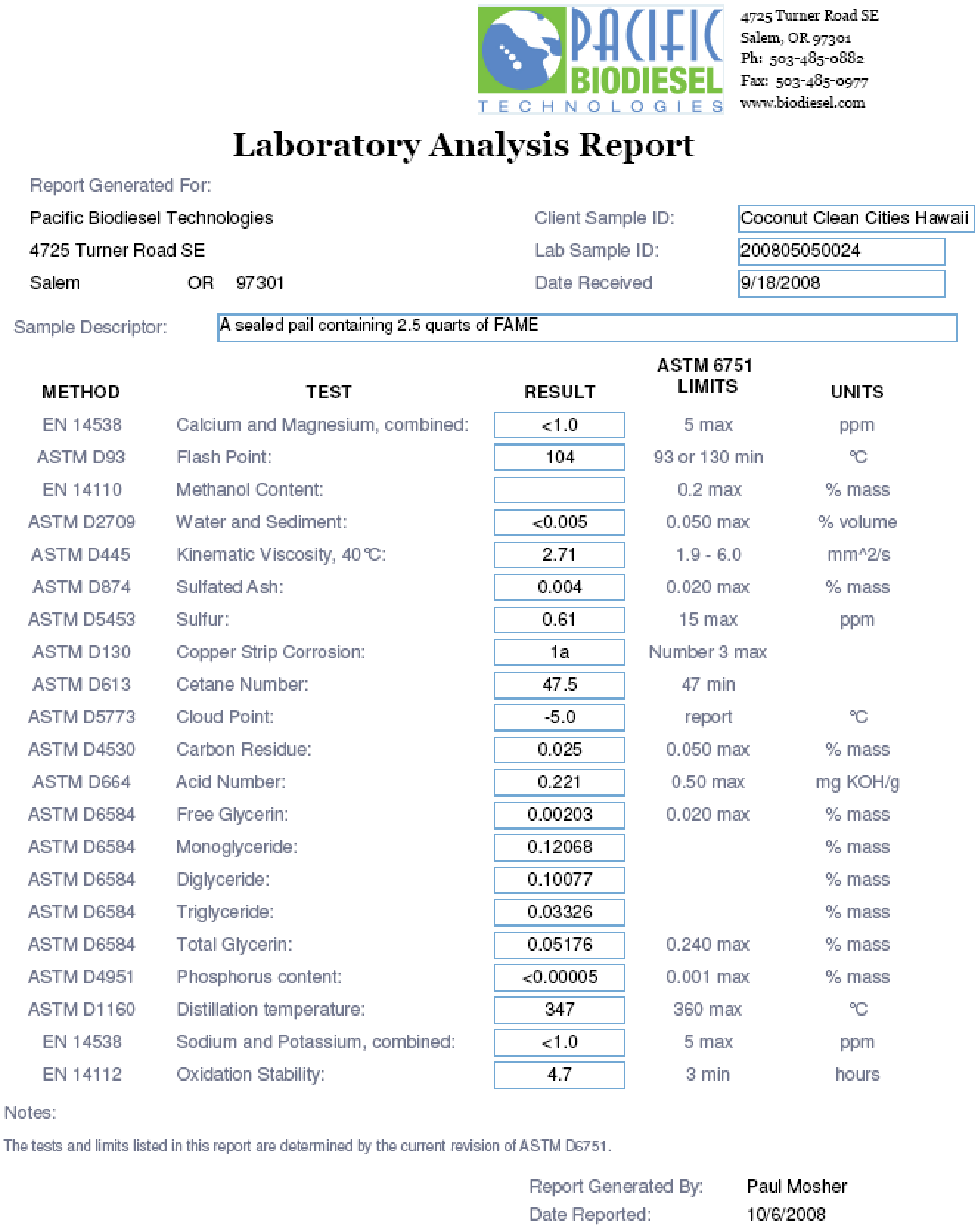
Sample Descriptor: Four PBTech supplied sample bottles, one liter each.

METHOD	TEST	RESULT	ASTM 6751 LIMITS	UNITS
EN 14538	Calcium and Magnesium, combined:	0.6	5 max	ppm
ASTM D93	Flash Point:	162	130 min	°C
ASTM D2709	Water and Sediment:	<0.005	0.050 max	% volume
ASTM D445	Kinematic Viscosity, 40°C:	4.85	1.9 - 6.0	mm^2/s
ASTM D874	Sulfated Ash:	<0.001	0.020 max	% mass
ASTM D5453	Sulfur:	5.49	15 max	ppm
ASTM D130	Copper Strip Corrosion:	1a	Number 3 max	
ASTM D613	Cetane Number:		47 min	
ASTM D5773	Cloud Point:	4.6	report	°C
ASTM D4530	Carbon Residue:	0.02	0.050 max	% mass
ASTM D664	Acid Number:	0.163	0.50 max	mg KOH/g
ASTM D6584	Free Glycerin:	<0.001	0.020	% mass
ASTM D6584	Monoglyceride:	0.255		% mass
ASTM D6584	Diglyceride:	0.183		% mass
ASTM D6584	Triglyceride:	0.372		% mass
ASTM D6584	Total Glycerin:	0.132	0.240	% mass
ASTM D4951	Phosphorus content:	0.00015	0.001 max	% mass
ASTM D1160	Distillation temperature:		360 max	°C
EN 14538	Sodium and Potassium, combined:	<1.4	5 max	ppm
EN 14112	Oxidation Stability:	7.9	3 min	hours

Notes:

The tests and limits listed in this report are determined by the current revision of ASTM D6751.

Report Generated By: P. Mosher
Date Reported: 6/9/2008



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Laboratory Analysis Report

Report Generated For:

Pacific Biodiesel Technologies
4725 Turner Road SE
Salem OR 97301

Client Sample ID:	Coconut Clean Cities Hawaii
Lab Sample ID:	200805050024
Date Received	9/18/2008
Sample Descriptor:	A sealed pail containing 2.5 quarts of FAME

METHOD	TEST	RESULT	ASTM 6751 LIMITS	UNITS
EN 14538	Calcium and Magnesium, combined:	<1.0	5 max	ppm
ASTM D93	Flash Point:	104	93 or 130 min	°C
EN 14110	Methanol Content:		0.2 max	% mass
ASTM D2709	Water and Sediment:	<0.005	0.050 max	% volume
ASTM D445	Kinematic Viscosity, 40°C:	2.71	1.9 - 6.0	mm^2/s
ASTM D874	Sulfated Ash:	0.004	0.020 max	% mass
ASTM D5453	Sulfur:	0.61	15 max	ppm
ASTM D130	Copper Strip Corrosion:	1a	Number 3 max	
ASTM D613	Cetane Number:	47.5	47 min	
ASTM D5773	Cloud Point:	-5.0	report	°C
ASTM D4530	Carbon Residue:	0.025	0.050 max	% mass
ASTM D664	Acid Number:	0.221	0.50 max	mg KOH/g
ASTM D6584	Free Glycerin:	0.00203	0.020 max	% mass
ASTM D6584	Monoglyceride:	0.12068		% mass
ASTM D6584	Diglyceride:	0.10077		% mass
ASTM D6584	Triglyceride:	0.03326		% mass
ASTM D6584	Total Glycerin:	0.05176	0.240 max	% mass
ASTM D4951	Phosphorus content:	<0.00005	0.001 max	% mass
ASTM D1160	Distillation temperature:	347	360 max	°C
EN 14538	Sodium and Potassium, combined:	<1.0	5 max	ppm
EN 14112	Oxidation Stability:	4.7	3 min	hours

Notes:

The tests and limits listed in this report are determined by the current revision of ASTM D6751.

Report Generated By:	Paul Mosher
Date Reported:	10/6/2008

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Laboratory Analysis Report

Report Generated For:

Pacific Biodiesel Technologies
4725 Turner Road SE
Salem OR 97301

Client Sample ID: Kukui Clean Cities Hawaii
Lab Sample ID: 200805050027
Date Received 9/26/2008

Sample Descriptor: A sealed glass flask containing 500 ml of FAME

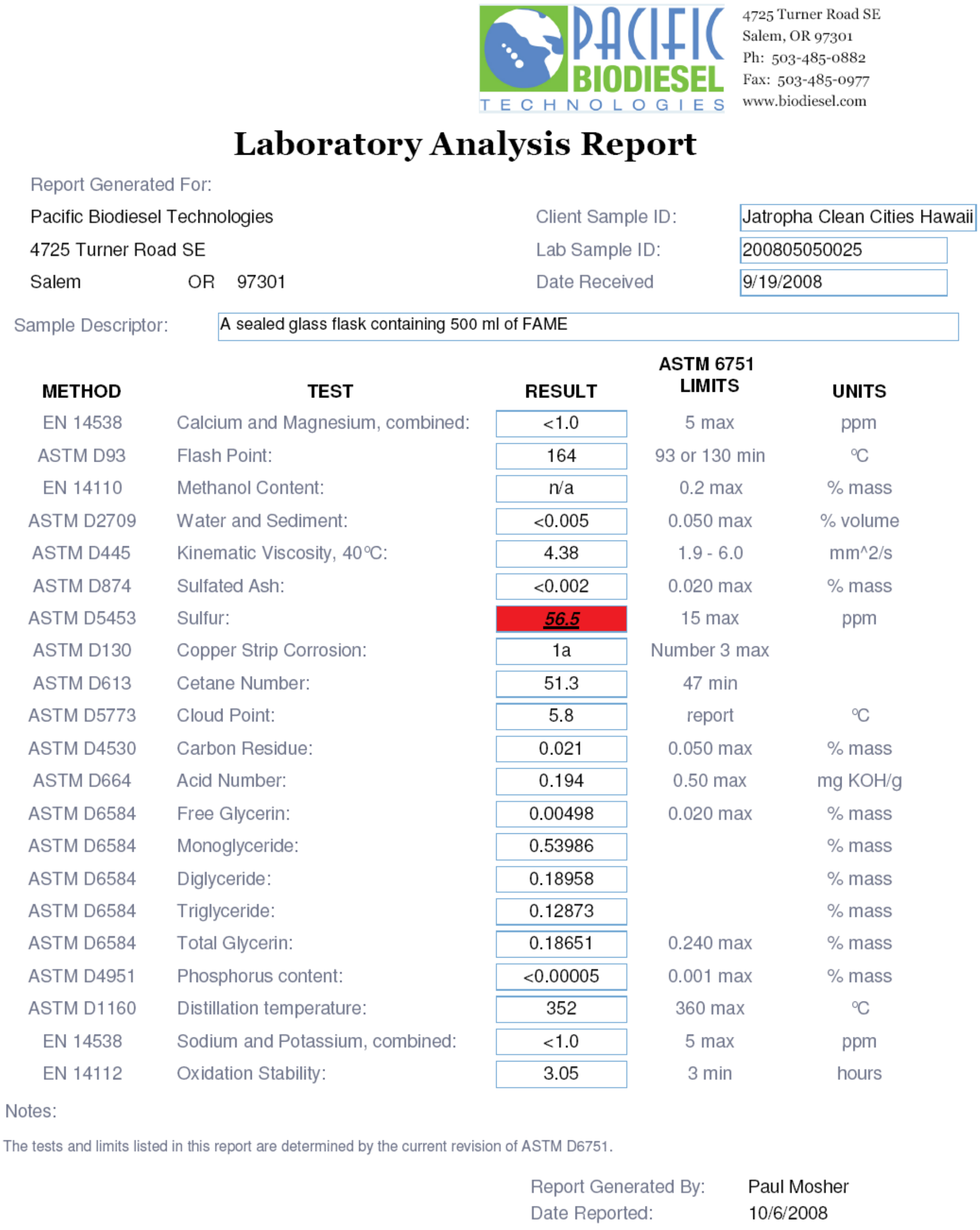
METHOD	TEST	RESULT	ASTM 6751 LIMITS	UNITS
EN 14538	Calcium and Magnesium, combined:	<2	5 max	ppm
ASTM D93	Flash Point:	166	93 or 130 min	℃
EN 14110	Methanol Content:	n/a	0.2 max	% mass
ASTM D2709	Water and Sediment:	<0.005	0.050 max	% volume
ASTM D445	Kinematic Viscosity, 40℃:	3.92	1.9 - 6.0	mm^2/s
ASTM D874	Sulfated Ash:	0.011	0.020 max	% mass
ASTM D5453	Sulfur:	5.9	15 max	ppm
ASTM D130	Copper Strip Corrosion:	1a	Number 3 max	
ASTM D613	Cetane Number:	***43.3***	47 min	
ASTM D5773	Cloud Point:	-7.8	report	℃
ASTM D4530	Carbon Residue:	***0.066***	0.050 max	% mass
ASTM D664	Acid Number:	0.370	0.50 max	mg KOH/g
ASTM D6584	Free Glycerin:	0.00663	0.020 max	% mass
ASTM D6584	Monoglyceride:	0.58263		% mass
ASTM D6584	Diglyceride:	0.08708		% mass
ASTM D6584	Triglyceride:	0.03906		% mass
ASTM D6584	Total Glycerin:	0.17463	0.240 max	% mass
ASTM D4951	Phosphorus content:	<0.00005	0.001 max	% mass
ASTM D1160	Distillation temperature:	355	360 max	℃
EN 14538	Sodium and Potassium, combined:	<5	5 max	ppm
EN 14112	Oxidation Stability:	3.1	3 min	hours

Notes:

The tests and limits listed in this report are determined by the current revision of ASTM D6751.

Report Generated By: Paul Mosher
Date Reported: 10/6/2008

Pacific Biodiesel Technologies



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Laboratory Analysis Report

Report Generated For:

Pacific Biodiesel Technologies
4725 Turner Road SE
Salem OR 97301

Client Sample ID: Jatropha Clean Cities Hawaii
Lab Sample ID: 200805050025
Date Received: 9/19/2008

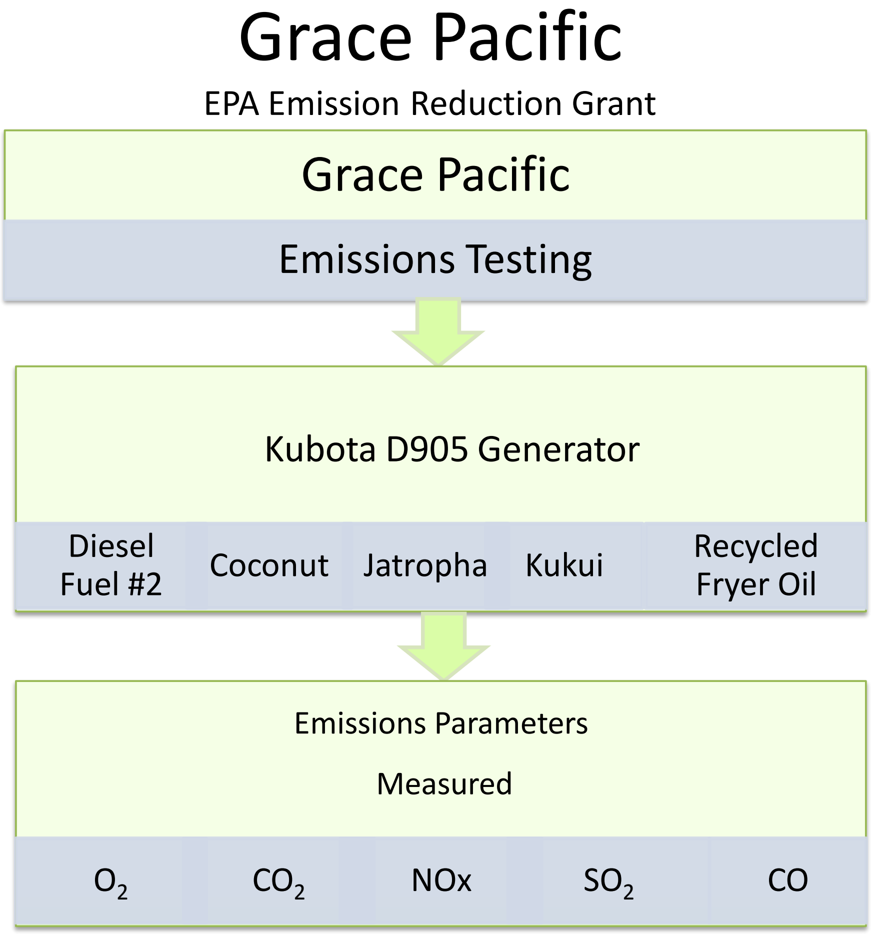
Sample Descriptor: A sealed glass flask containing 500 ml of FAME

METHOD	TEST	RESULT	ASTM 6751 LIMITS	UNITS
EN 14538	Calcium and Magnesium, combined:	<1.0	5 max	ppm
ASTM D93	Flash Point:	164	93 or 130 min	°C
EN 14110	Methanol Content:	n/a	0.2 max	% mass
ASTM D2709	Water and Sediment:	<0.005	0.050 max	% volume
ASTM D445	Kinematic Viscosity, 40°C:	4.38	1.9 - 6.0	mm^2/s
ASTM D874	Sulfated Ash:	<0.002	0.020 max	% mass
ASTM D5453	Sulfur:	***56.5***	15 max	ppm
ASTM D130	Copper Strip Corrosion:	1a	Number 3 max	
ASTM D613	Cetane Number:	51.3	47 min	
ASTM D5773	Cloud Point:	5.8	report	°C
ASTM D4530	Carbon Residue:	0.021	0.050 max	% mass
ASTM D664	Acid Number:	0.194	0.50 max	mg KOH/g
ASTM D6584	Free Glycerin:	0.00498	0.020 max	% mass
ASTM D6584	Monoglyceride:	0.53986		% mass
ASTM D6584	Diglyceride:	0.18958		% mass
ASTM D6584	Triglyceride:	0.12873		% mass
ASTM D6584	Total Glycerin:	0.18651	0.240 max	% mass
ASTM D4951	Phosphorus content:	<0.00005	0.001 max	% mass
ASTM D1160	Distillation temperature:	352	360 max	°C
EN 14538	Sodium and Potassium, combined:	<1.0	5 max	ppm
EN 14112	Oxidation Stability:	3.05	3 min	hours

Notes:

The tests and limits listed in this report are determined by the current revision of ASTM D6751.

Report Generated By: Paul Mosher
Date Reported: 10/6/2008



Grace Pacific

EPA Emission Reduction Grant

Grace Pacific

Emissions Testing

Kubota D905 Generator

Diesel Fuel #2	Coconut	Jatropha	Kukui	Recycled Fryer Oil

Emissions Parameters

Measured

O_2	CO_2	NOx	SO_2	CO

IV. Grace Pacific Corporation and GP Roadway Solutions – Biodiesel Emissions Testing

Joseph Shacat -- Grace Pacific
Chad Browning -- Environmental Science International, Inc.
Marvin Rivera – GP Roadway Solutions
Bryan Collins -- Pacific Biodiesel
Harry Johnson and Aaron Lord – SCEC Environmental

Abstract

On January 15, 2009 SCEC performed biodiesel emission testing on a Kubota D905, 5000 watt Generator located at the GP Roadway Solutions Facility. The testing consisted of one (1) sixty (60) minute gas sample run for each of the five (5) different types of fuel tested. The five (5) different fuels tested were (1) the #2 diesel used to blend the bio fuels to a concentration of 20% (B20), (2) coconut oil B20, (3) jatropha oil B20, (4) kukui nut oil B20 and (5) recycled fryer oil B20. The sampling runs occurred in the order listed above. Before each run the generator was operated using the specific fuel for that particular run for a period of time that allowed the unit to reach it's peak operating temperature (warmed up) and to insure that the fuel delivery system was completely primed (purely operating on the particular fuel that was being tested). Before and after each sample run all gas analyzers were quality assurance calibrated and all data collected during each run was corrected based on the results of the calibrations. During each sample run, a gas sample was extracted from the exhaust of the generator and was delivered to analyzers inside of SCEC's mobile emission laboratory (MEL). The gas sample was then analyzed for O_2, CO_2, NOx, CO and SO_2 following USEPA 40CFR Part 60 methods 3a, 6c, 7e and 10.

The purpose of the testing was twofold. (1) To determine if these various biofuels can be a viable alternative compared to commercially available diesel fuel and (2) to document and compare emissions resulting from an engine that is running on the various bio fuels included in this testing report.

This testing was completed as part of the "Biodiesel from Fuel Crops in Hawaii" EPA grant awarded to Honolulu Clean Cities in partnership with Pacific Biodiesel, Oceanic Institute, Aloha Green, Hawaii Agricultural Research Center and Maui Cattle Company. The overall goal of the project is to evaluate a variety of locally grown source materials as potential feedstocks for biodiesel production.

Mr. Joseph Shacat – Grace Pacific (GP) Environmental Manager and Chad Browning – Environmental Science International (ESI) Environmental Scientist provided on-site test coordination for Grace Pacific. Mr. Marvin Rivera – GP Roadway Solutions (GPRS) Manager provided the site location and generator along with the technical expertise to make the generator operate using the various fuels that were tested. Mr. Bryan Collins of Pacific Biodiesel (PBD) provided the diesel and biodiesel fuels used and coordinated the onsite fuel blending. Source testing personnel for SCEC were Harry Johnson - Project Manager and Aaron Lord – Environmental Specialist. No observers from either governing agency were

on-site during the test program. This test report presents the sampling methodology, data, calculations, and results.

All raw data from the field sampling program was combined with the analytical results into the appropriate equations from the applicable methods to determine the final results as listed in Section 4. The calculations were performed using computer programs that have undergone quality control inspections before usage. Detailed results (and supporting data) are provided in Appendix A. Plant operating condition, quality assurance, test methods, and example calculations are contained in Appendices B through E, respectively.

Equipment Description

The GP Roadway Solutions owned diesel generator is a Kubota D905, Serial #: 17P1795. This generator delivers a maximum output of 5000 watts and powers up four (4) 1250 watt metal halide flood lights. Typically this piece of equipment is used for night work on road construction projects and is exempt from State of Hawaii Department of Health (DOH) source testing requirements. However, this generator was chosen based on its dry priming capabilities and its low fuel consumption demand of approximately 0.6 gallons per hour (GPH).

Test Description

Test Conditions

The Kubota D905 generator was operated at a steady load throughout each test run with the exception being run #3. During run #3 the generator tripped off-line at 13:24, forty (40) minutes into the run. The generator was restarted, inspected and warmed up for a period of twenty six (26) minutes and sampling resumed at 13:50 and the remaining 20 minutes of the run was recorded. The valid data (not including the 26 minute interruption) maintained integrity and consistency despite the interruption. During each run of the emissions testing the generator was operated at the maximum 5000 watt output (all four 1250 watt lights on) and the fuel flow rate was accurately calculated by making before and after volume measurements of the fuel with a graduated cylinder. Plant load and fuel usage were monitored and recorded, this data is presented in the Summary of Results, Table 4.1.

All required quality assurance protocols were met. All instrument calibrations were well within the stipulated method requirements.

Sample Locations

All samples were collected from the exhaust pipe located on top of the generator housing approximately five feet (5’) from ground level.

Test Procedures

The test procedures and sampling log used for the exhaust measurements are summarized below in Tables 3.1 and 3.2, respectively. The procedures selected are consistent with EPA source test methods. Brief discussions of each procedure are provided in Appendix D.

Table 3.1

Test Procedures

Parameter	Method	No. of Runs	Duration
O_2/CO_2	EPA Method 3a	1 run per fuel	60 min each
NOx	EPA Method 7e	1 run per fuel	60 min each
CO	EPA Method 10	1 run per fuel	60 min each
SO2	EPA Method 6c	1 run per fuel	60 min each

Table 3.2

Sampling Log

Run No.	*Parameters Measured* *Asphalt Plant Backup Generator*	**Date**	**Time**
1	O_2/CO_2/ NOx/CO/SO2	01/15/09	09:25 – 10:25
2	O_2/CO_2/ NOx/CO/SO2	01/15/09	11:00 – 12:00
3	O_2/CO_2/ NOx/CO/SO2	01/15/09	12:43 – 14:10
4	O_2/CO_2/ NOx/CO/SO2	01/15/09	14:40 – 15:40
5	O_2/CO_2/ NOx/CO/SO2	01/15/09	16:10 – 17:10

Summary of Results

The results of the emissions test program are summarized in Table 4.1. Emissions results for NOx, CO, and SO2 are provided in Lb/Hr for Diesel Fuel, Coconut Oil B20, Jatropha Oil B20, and Recycled Fryer Oil B20. Emissions results in lb/hr allow for a direct comparison between the different fuels, as this corrects for fuel flow and fuel calorific value, which varied based on individual test conditions and the type of fuel. Emissions results for Kukui Nut Oil B20 could not be calculated in lb/hr because there was insufficient kukui nut biodiesel to determine the fuel calorific value.

Table 4.1

Kubota D905 Generator Serial #: 7P1795 – Summary of Results – O2, CO2, NOx, CO and SO2

Parameter	Units	Diesel Fuel #2	Coconut Oil B20	Jatropha Oil B20	Kukui Nut Oil B20	Recycled Fryer Oil B20	Average
NOx	ppmvd	326.73	320.79	311.69	325.14	324.51	319.74
	ppmvd @ 15% O2	179.15	176.56	171.26	177.39	179.37	175.65
	Lb/MMBtu	0.694	0.681	0.658	0.683	0.692	0.678
	Lb/Hr	4.78E-02	4.22E-02	3.96E-02	N/A	4.09E-02	4.32E-02
CO	ppmvd	83.52	88.18	84.24	91.79	84.73	85.31
	ppmvd @ 15% O2	45.79	48.53	46.28	50.08	46.83	46.87
	Lb/MMBtu	0.108	0.114	0.108	0.117	0.110	0.110
	Lb/Hr	7.430E-03	7.058E-03	6.512E-03	N/A	6.498E-03	7.000E-03
SO_2	ppmvd	0.82	0.78	0.93	0.70	0.73	0.85
	ppmvd @ 15% O2	0.45	0.43	0.51	0.38	0.40	0.46
	Lb/MMBtu	0.002	0.002	0.003	0.002	0.002	0.002
	Lb/Hr	1.678E-04	1.422E-04	1.653E-04	N/A	1.274E-04	1.584E-04
O_2	%	10.14	10.18	10.16	10.09	10.23	10.16
CO_2	%	7.97	7.97	8.01	8.06	7.93	7.98
Fuel Calorific Value	Btu/Gal	139,419	116,459	121,289	N/A	121,218	N/A
Volume Flow	DSCFM	20.41	18.36	17.73	0.00	17.59	18.83
Fuel Flow	Gal/Min	0.0082	0.0076	0.0073	0.0072	0.0072	0.0077
Electric Output	Watts	5000	5000	5000	5000	5000	5000

N/A: Not applicable. Insufficient fuel was available to obtain fuel calorific value, which is used to calculate Lb/Hr.

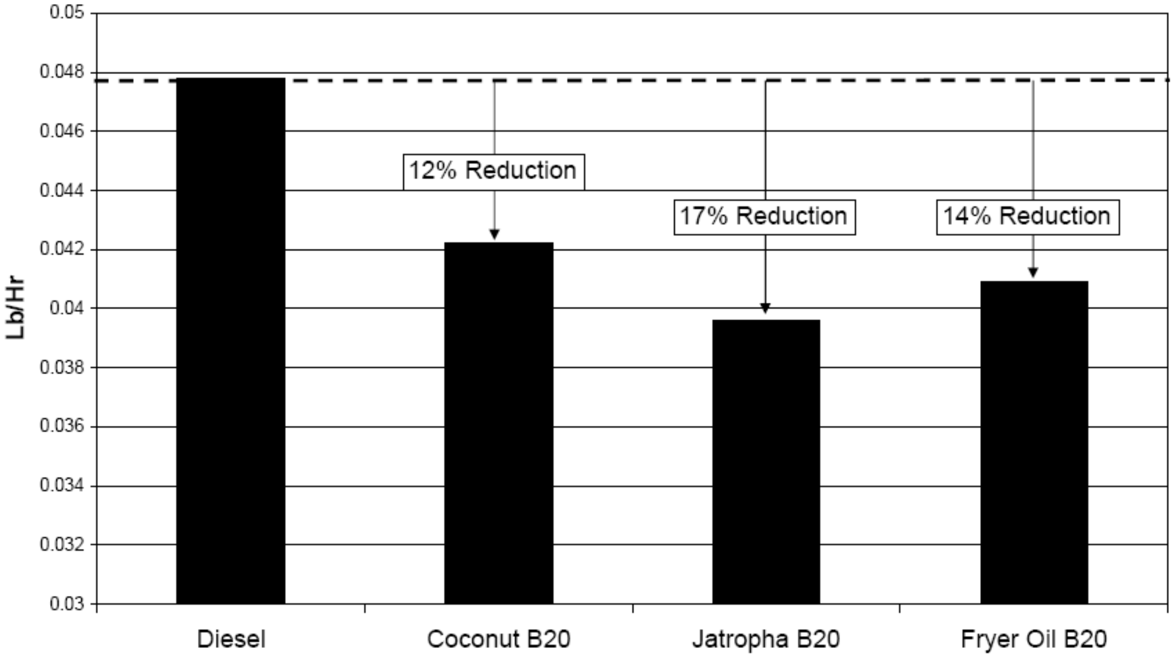
The emissions values reported here in lb/hr are not directly comparable to previously published EPA studies and emissions factors, which report emissions in g/bhp/hr. In order to report emissions in g/bhp/hr, testing would have to incorporate the use of a dynamometer, which is beyond the scope of this study. Nonetheless, these data are useful in comparing the fuels associated with this study.

Emissions of NOx, CO, and SO2 were higher for Petroleum Diesel Fuel than for B20 blends of Coconut Oil Biodiesel, Jatropha Oil Biodiesel, and Recycled Fryer Oil B20 (Table 4.1 and Figures 4.1 - 4.3). Emissions reductions for NOx ranged from 12-17%, reductions for CO ranged from 5-13%, and reductions for SO2 ranged from 1-24%.

NOx emissions associated with biodiesel have shown conflicting results depending on the type of engine used, the biodiesel feedstock, and fuel additives. A thorough review of the effects of biodiesel blends on vehicle emissions (NREL 2006) demonstrated that, on average, biodiesel has no significant impacts on NOx emissions. It is important to note that the NREL (2006) study focused primarily on heavy duty vehicle emissions (i.e., buses and trucks). The engine tested in this study was quite small in comparison. The NOx emissions associated with the biodiesel blends tested here showed significant reductions compared to petroleum diesel (Figure 4.1).

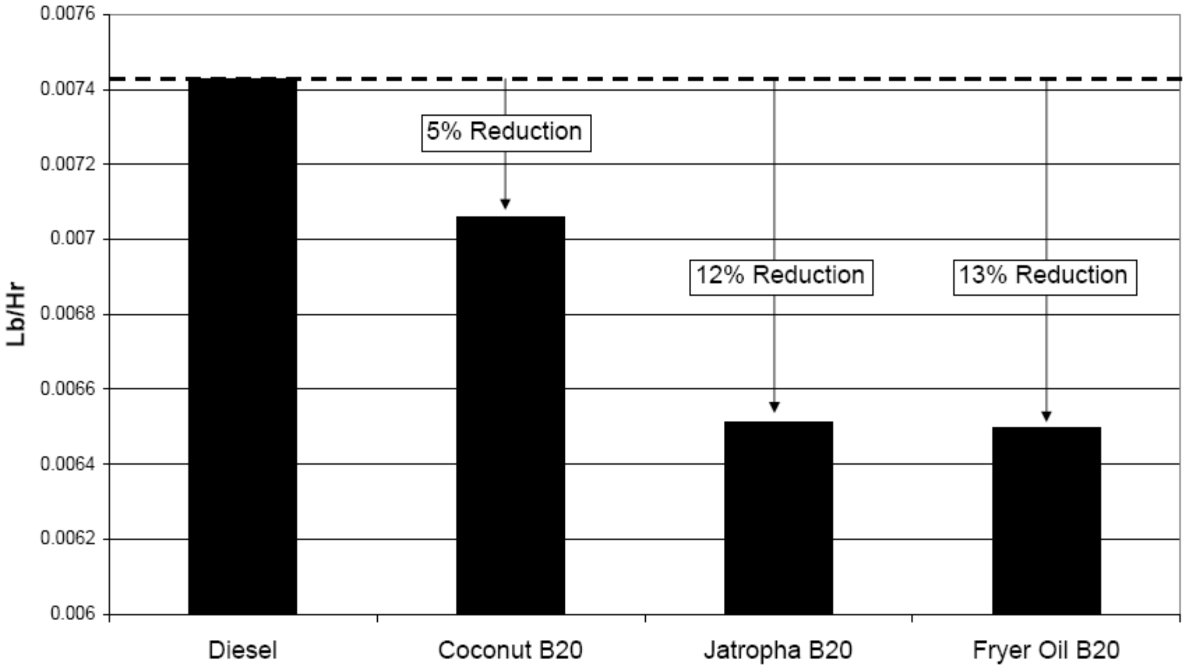
[National Renewable Energy Laboratory, October 2006. Effects of Biodiesel Blends on Vehicle Emissions: Fiscal Year 2006 Annual Operating Plan Milestone 10.4. R.L. McCormick, A. Williams, J. Ireland, M. Brimhall, and R.R. Hayes. NREL/MP-540-40554.]

Figure 4.1
NOx Emissions



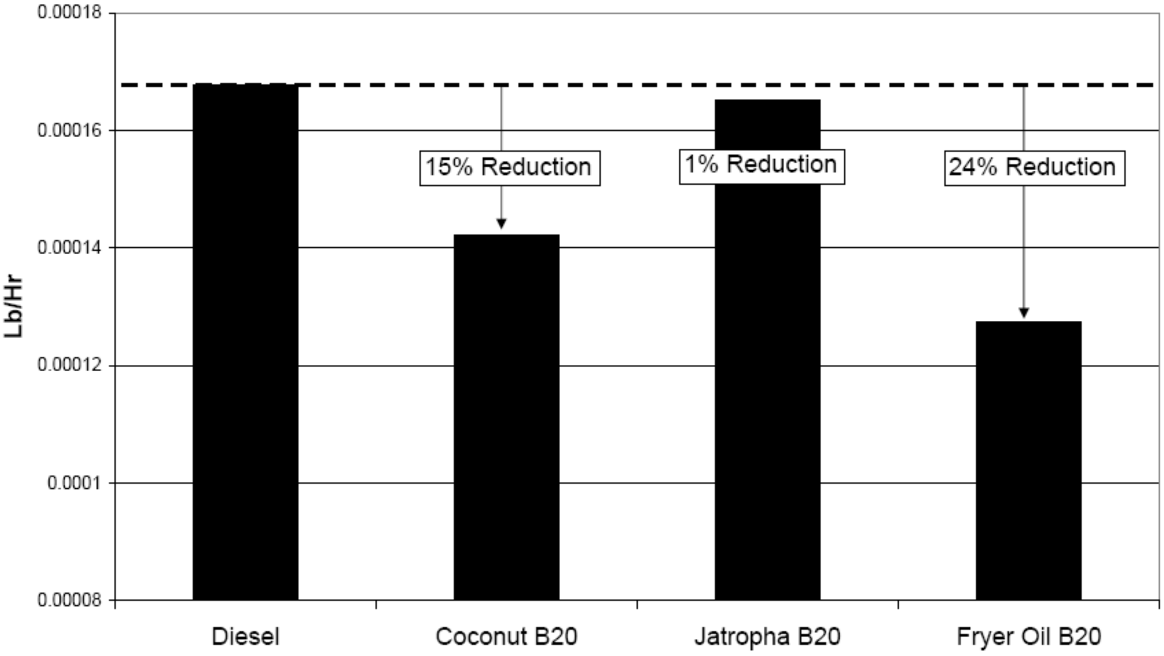
Reductions in CO emissions, along with reductions in PM and HC emissions (not analyzed in this study), have been well documented for diesel engines burning various blends of biodiesel. The added oxygen content of the biodiesel allows for more complete combustion of the fuel, thereby reducing CO, PM, and HC emissions. The reduced CO emissions associated with the biodiesel blends tested here (Figure 4.2) support previous studies that show lower CO emissions for biodiesel.

Figure 4.2
CO Emissions



SO2 emissions are largely a function of the sulfur content of the fuel itself. For example, Jatropha Oil Biodiesel had a sulfur content of 56.5 ppm, which exceeds the ASTM 6751 limit of 15 ppm (Section III) as well as the federal limit for the sulfur content of highway diesel fuel of 50 ppm. Jatropha Oil B20 had the highest SO2 emissions of the biodiesel blends tested in this study (Figure 4.3).

Figure 4.3
SO_2 Emissions



Note: Please see Grace Pacific Corporation Report for appendices with Detailed Results and Supporting Data, Photographic Images, Quality Assurance, Test Methods, and Fuel Oil Analysis.

V. Lessons Learned

Collaboration

The project as a whole took longer than anticipated, in large part due to the fact that it was a collaborative project. Initially Aloha Green, Hawaii Agriculture Research Center and Maui Cattle Company were considering partnering on the project, but decided against it as the scope of the project evolved.

Seed and Nut Processing & Analysis

The project showed that island nuts and oilseeds can be processed into oils for conversion into biodiesel fuel and there are uses for the presscake probably as a ruminant (cattle) feed. However the quantities (100kg) of coconut, kukui nut and jatropha seeds were not enough feedstock material to get a sustained processing run for accurate data acquisition. With only a 100kg of feedstock it was impossible to optimize a single oil extraction run per feedstock. More feedstock material would have provided replicated runs, and optimizing oil extraction could have been run. An estimate of a ton more of product was needed to get accurate readings for these various feedstocks. Currently, there is not that much product available locally. To become an economic reality there is still a long way to go before the use of locally grown oilseed and nuts can be pressed into oil for the conversion of biodiesel fuels.

The small sample size available demonstrates need for this grant. If it had been easy to procure biofuel feedstock in Hawaii, it would already be utilized and there would not have been need for assistance and research. Although the quantity of fuel produced during this project was very small, many lessons were learned about procuring and processing feedstock in Hawaii. Obtaining the 100kg samples used for the project was more difficult and time-consuming than originally expected, however the participants in the study now have useful contacts for future feedstock access.

An important industry application was learned about the processing of feedstock. There is no need to hand crack kukui shells, which takes considerable time and energy, because the oil content of these nuts is so high that additional fiber is needed to use the oil press efficiently. A best future practice would be to process the whole nuts in a Hammermill and put the entire contents through the oil press. Further testing would be needed to see if shell content in resulting presscake would be useable for animal feed. If not, other uses such as mulch are a possibility.

Oil Characterization, Biodiesel Processing & Analysis

Overall, coconut oil is a fine feedstock for biodiesel production. The kukui methyl ester sample failed two parameters of ASTM D6751, cetane number and carbon residue. Therefore, it cannot be considered biodiesel. Other than the high sulfur content, jatropha oil would be a fine feedstock for biodiesel production.

Biodiesel Emissions Testing

Emissions of NOx, CO, and SO2 were higher for Petroleum Diesel Fuel than for B20 blends of Coconut Oil Biodiesel, Jatropha Oil Biodiesel, and Recycled Fryer Oil B20. Emissions reductions for NOx ranged from 12-17%, reductions for CO ranged from 5-13%, and reductions for SO2 ranged from 1-24%.

Reductions in CO emissions, along with reductions in PM and HC emissions (not analyzed in this study), have been well documented for diesel engines burning various blends of biodiesel. The added oxygen content of the biodiesel allows for more complete combustion of the fuel, thereby reducing CO, PM, and HC emissions. The reduced CO emissions associated with the biodiesel blends tested here support previous studies that show lower CO emissions for biodiesel.

Jatropha Oil Biodiesel had a sulfur content of 56.5 ppm, which exceeds the ASTM 6751 limit of 15 ppm as well as the federal limit for the sulfur content of highway diesel fuel of 50 ppm. Jatropha Oil B20 had the highest SO2 emissions of the biodiesel blends tested in this study.

The NOx results were surprising, as high NOx content is typically sited as a reason against use of biofuels. The ramifications for industry are the ability to operate plants <u>longer</u> with biodiesel, since NOx is one of the two main limits to operational hours.

VI. Next Steps

Further study, including larger sample sizes and greater repetitions, is needed in order to produce publishable results to share with the scientific community.

Further study of all three feedstock crops is likely, particularly jatropha and kukui which have generated the most interest from the private sector. There are already small plots of jatropha being grown by farmers and researchers on Oahu and the Big Island with additional plantings scheduled. Kukui thrives in the wild on most of the Hawaiian islands, therefore collection of kukui nuts for further study is feasible, as are the prospects for cultivation. There are no known plans for cultivating coconuts for biodiesel production, although the possibilities for this feedstock are strong throughout the Pacific Rim.

In considering which crops to plant for biodiesel, it will be important to evaluate potential co-products. Jatropha, for example, has toxic properties which require further processing to be used as a suitable feed for animals (which may affect the health of the animals themselves and also taste and toxicity of the animals as a human food source). It is possible that the natural toxicity in jatropha, on the other hand, could be used as a repellent, for example to keep birds, rats and wild pigs away from crops.

Honolulu Clean Cities will continue to promote use of non-petroleum-based transportation fuels. There is also focus on biofuels at a state level. The State of Hawaii Department of Business, Economic Development & Tourism (DBEDT) was tasked to prepare a bioenergy master plan in consultation with representatives of the relevant stakeholders. The primary objective of the bioenergy master plan is to develop a Hawaii renewable biofuels program to manage the State's transition to energy self-sufficiency based in part on biofuels for power generation and transportation. Issue-focused meetings have taken place, and a draft plan review meeting is tentatively planned for July 2009. A full report to the Hawaii Legislature is planned for December 2009.