COMPARATIVE LIFE CYCLE ASSESSMENT OF COCONUT BIODIESEL AND CONVENTIONAL DIESEL FOR PHILIPPINE AUTOMOTIVE TRANSPORTATION AND INDUSTRIAL BOILER APPLICATION

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INTRODUCTION

The world's energy consumption is estimated to be 3.36×10^{20} J per annum and is projected to increase to up to 6.3×10^{20} J in the year 2050[2]. Due to this high demand, energy shortage poses specific risks on the transportation sector and some industries that are dependent on liquid fuels such as diesel. This considerable demand for petroleum also implies significant levels of air pollution. In the Philippines, Metropolitan Manila was ranked as 2nd dirtiest city in Asia in 2002[3]. Using an alternative fuel is one of the options that could possibly solve these environmental problems, but the extent of its environmental advantage is still to be studied and compared to conventional diesel. Different biofuels were already developed and used in many parts of the world and the most popular is the biodiesel, which is an alternative to petroleum diesel. Biodiesel can be obtained from tree crops, such as palms, coconuts, and olives[4]. This creates a great potential in the Philippines since it can supply up to 60% of the world's coconut oil market[5]. This study quantitatively assessed the total environmental impacts from emissions and energy consumptions of coconut biodiesel and petroleum or conventional diesel from the raw materials to the final use using environmental life cycle assessment (LCA). Matrix-based[6] calculations are used for the Life Cycle Inventory (LCI), which are coded in Microsoft Excel spreadsheet environment. The Life Cycle Impact Assessment (LCIA) was performed through the use of critical volumes method and ecological footprint. Input data for model calibration are derived from theoretical mass and energy balances, technical publications, industry average values and government databases. The model covers both automotive transport and industrial boiler applications. The sensitivity analysis presented four scenarios that will assess the effect of data uncertainty on the model. Validation of the results with other established models like the EDIP and FRED were also included.

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[2] Komiyama, H., Mitsumori, T., Yamaji, K. and Yamada, K. (2001). Assessment of Energy Systems by Using Biomass Plantation. Fuel 80: 707 – 715.

[3] Gallardo, S. (2002). Air Quality Monitoring in Metro Manila: De La Salle University Program for Clean Air. Guillermo Guevarra III Professional Chair Lecture. Manila, Philippines.

[4] Cadenas, A. and Cabezudo, S. (1998). Biofuels and Sustainable Technologies: Perspectives for Less Developed Countries. Technological Forecasting & Social Change 58: 83 – 103.

[5] Carandang, E. V. and Philippine Coconut Research & Development Foundation, Inc. (2002). Coconut Biofuels: An Environmental & Economic Alternative. Alternative Fuels in the Philippines. Manila, Philippines.

[6] Heijungs, R. and Suh, S. (2002). The Computational Structure of Life Cycle Assessment. Kluwer, Dordrecht.

THE LCA METHODOLOGY

1. ***Goal and Scope Definition***[7] **-** The goal of this study is to conduct a comparative environmental life cycle assessment to quantify and compare the comprehensive sets of environmental flows (to and from the environment) associated with both biodiesel and conventional diesel, over their entire life cycles for application in the automotive transportation and industry (industrial boilers) sector.

The following are some of the major assumptions made in the model.

- Some emissions data and other relevant data were taken from an established software tool such as ***G***reenhouse Gases, ***R***egulated ***E***missions, and ***E***nergy Use in ***T***ransportation or **GREET** v1.5a.
- The current energy mix scenario from the Philippine Energy Plan[8] was used.
- The model assumes either 100% or 0% coconut residues utilization for power and heat generation.
- The agricultural productivity of coconut oil in the Philippines is 0.0421 kg/m^2-a.
- Air emissions and energy consumption (coal, natural gas and petroleum) are the only consideration of the inventory.
- Mean values for conversion efficiencies, heating values, and other inputs are used in the model.

2. ***Inventory Analysis***[9] **-** The entire life cycle inventory processes are specified below,

- **Project Parameter -** The LCI will cover mass and energy balances for coconut biodiesel and conventional diesel.
- **Product Parameter -** The products will be assessed using the same and equal basis called the functional unit. In this model, the functional unit used is 1 kilometer of travel for automotive transportation use and 1 kilogram of steam for industrial boiler use.
- **Process Parameter**

A. Coconut Biodiesel

The primary feedstock used for biodiesel production in the Philippines is the coconut. The extracted coconut oil is transesterified using methanol and sodium hydroxide as catalyst to form the coconut methyl ester and a by-product glycerol. Methanol was chosen instead of ethanol due to its availability, less expensive as compared to ethanol but provides same process efficiencies**[10]**.

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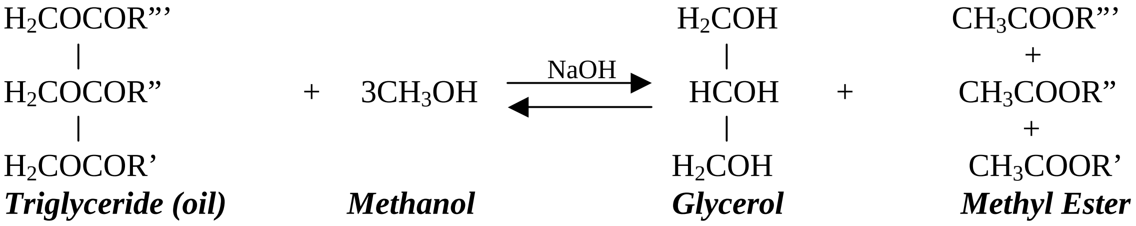
[7] ISO 14041 (1998). Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis. International Organization for Standardization, Geneva.

[8] Philippine Department of Energy - Philippine Energy Plan (2002-2011).

[9] ISO 14041 (1998). Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis. International Organization for Standardization, Geneva.

[10] Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. and Shapouri, H. (1998). Final Report: Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. NREL/SR-580-24089 UC Category 1503.

The reaction of the coconut oil or the triglycerides with the methanol is shown in Figure 1.



$$\begin{array}{ccccccc} \mathrm{H_2COCOR'''} & & & & \mathrm{H_2COH} & & \mathrm{CH_3COOR'''} \\ | & & & & | & & + \\ \mathrm{H_2COCOR''} & + & \mathrm{3CH_3OH} & \xrightleftharpoons{\mathrm{NaOH}} & \mathrm{HCOH} & + & \mathrm{CH_3COOR''} \\ | & & & & | & & + \\ \mathrm{H_2COCOR'} & & & & \mathrm{H_2COH} & & \mathrm{CH_3COOR'} \\ \textit{Triglyceride (oil)} & & \textit{Methanol} & & \textit{Glycerol} & & \textit{Methyl Ester} \end{array}$$

Figure 1 **Transesterification Reaction**

The following processes in Figure 2 are the step-by-step procedure in the manufacture of coconut biodiesel.

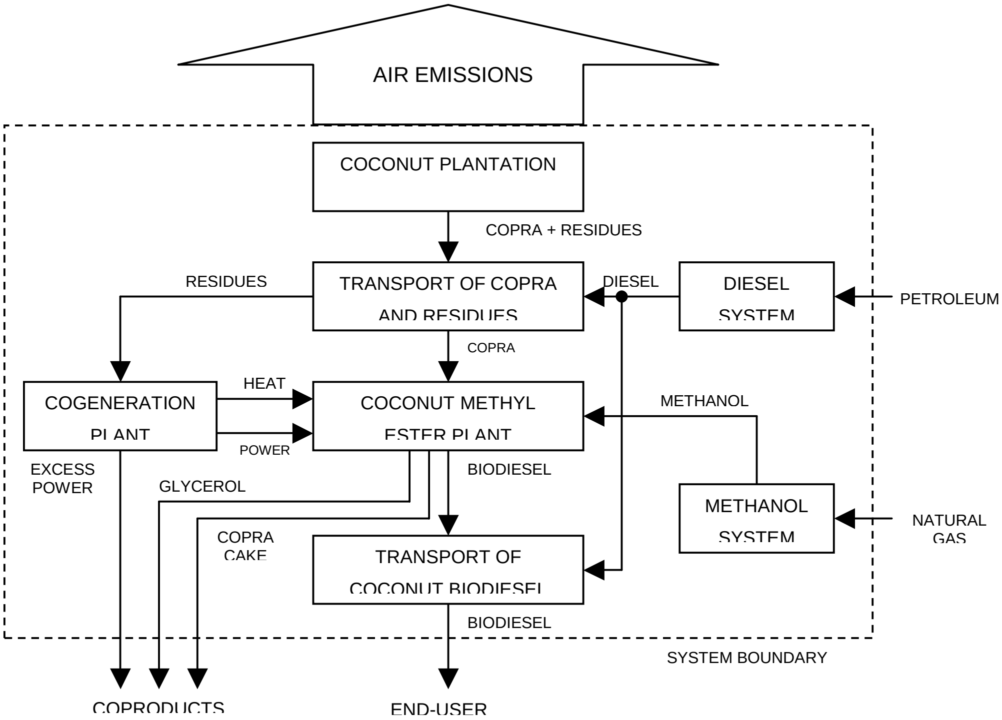


Figure 2 **Coconut Biodiesel Process Flowchart**

Coconut oil expression and transesterification together with some related industrial data were characterized with the cooperation of oil industries in the Philippines, which produces coconut oil methyl ester (COME).

B. Petroleum Diesel

The petroleum diesel used for the model contains already 0.05% maximum sulfur content due to the provision of the Philippine Clean Air Act of 1999**[11]**. Conventional diesel manufacturing process from series of distillation is assumed in this study.

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[11] Philippine Clean Air Act, Implementing Rules and Regulations, 1999.

- **LCA Parameter**

The data uncertainty analysis includes the sensitivity analysis of the model inputs. Four scenarios are used in the model:
Scenario 1: Automotive Transport Application with Coproduct Utilization
Scenario 2: Automotive Transport Application without Coproduct Utilization
Scenario 3: Industrial Boiler Application with Coproduct Utilization
Scenario 4: Industrial Boiler Application without Coproduct Utilization

In this study, several data have been combined for each stage in the life cycle of the coconut biodiesel. These stages include the raw materials extraction, production, energy consumption, transport, use and disposal. In a matrix type model, process data are tabulated based on commodities and the process it undergoes. The commodities consist of economic (inter-industry flows, such as steel, electricity, products, and waste-to-be-processed) and ecologic or environmental (natural resources, emissions, others)[12]. The economic commodities, which forms part of the technology matrix, includes electricity, steam, oil, solid waste, coconut biodiesel, glycerol, methanol, copra, coconut husk and shell. Likewise, the ecologic commodities, which forms part of the intervention matrix, includes Petroleum, Natural Gas, Volatile Organic, Compounds (VOC), Carbon Monoxide (CO), Nitrogen Oxides (NOx), Particulate Matter (PM10), Sulfur Oxides (SOx), Methane (CH_4), Nitrous Oxides (N_2O), Carbon Dioxide (CO_2).

A sample technology matrix within the model is shown in Table 1. Transportation accounts were included in each stage of the process. The numbers in the parenthesis indicates the partitions used for the process for co-product allocation.

Table 1 **The Technology Matrix**

Stages	**Electricity Production**	**Steam Production**	**Oil Extraction (1)**	**Oil Extraction (2)**	**Biodiesel Production (1)**	**Biodiesel Production (2)**	**Methanol Production**	**Coconut Farming (1)**	**Coconut Farming (2)**
Electricity (MJ)	1.000	0.000	-0.218	-0.109	-0.078	-0.011	-0.022	0.000	0.000
Steam (MJ)	0.000	1.000	-25.47	-12.735	-0.409	-0.059	0.000	0.000	0.000
Coconut Oil (kg)	0.000	0.000	1.000	0.000	-0.875	-0.125	0.000	0.000	0.000
Solid Waste (kg)	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
Biodiesel (kg)	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
Glycerol (kg)	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Methanol (kg)	0.000	0.000	0.000	0.000	-0.125	-0.018	1.000	0.000	0.000
Copra (kg)	0.000	0.000	-1.027	-0.513	0.000	0.000	0.000	1.000	0.000
Coconut Husk and Shell (kg)	-0.140	-0.073	0.000	0.000	0.000	0.000	0.000	0.000	1.000

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[12] Heijungs, R. (1996). Key Issues in Improving Life Cycle Assessment. Journal of Cleaner Production. Vol. 4, No. 3 – 4.

3. ***Impact Assessment***[13] - The impact assessment was performed using the critical volumes method[14] introduced by Vignes to determine the total emissions impact and the ecological footprint[15] introduced by Wackernagel to determine the total energy consumption impact. For critical volumes method, pollution factor (PF) and environmental impact units (EIU) are used wherein PF can be derived from the limiting concentrations for potential pollutants and EIU is a dimensionless number on relative environmental impact. On the other hand, the energy resource footprint can be derived based from their productivity yield. Figures 3 and 4 shows a sample result of impact assessment for scenario 1 (automotive application with coproduct allocation).

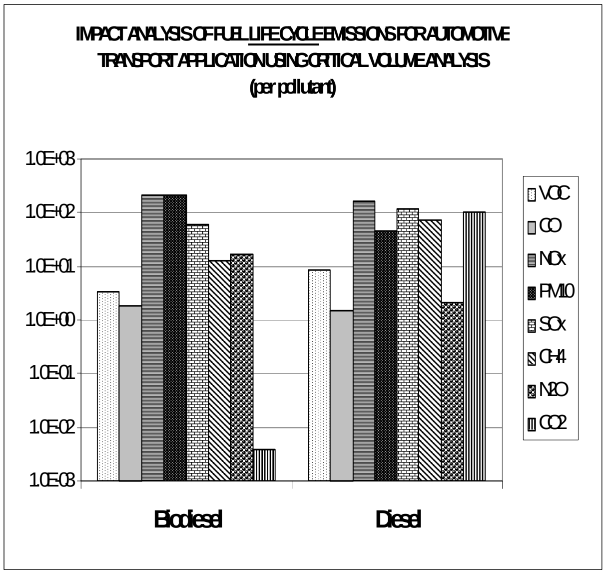

Figure 3 **Scenario 1 Total Emissions Impacts for Automotive Transport**

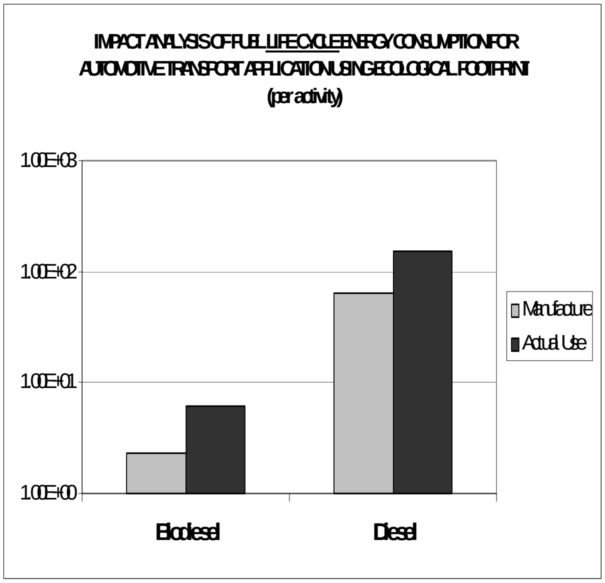

Figure 4 **Scenario 1 Total Energy Impacts for Automotive Transport**

4. ***Interpretation***[16] - The result of the life cycle assessment for coconut biodiesel and diesel shows that the use of coconut biodiesel in the Philippines can be applicable. Although, the use of coconut residues for power cogeneration slightly increases some of the emissions such as CO, NOx, and PM_{10}, still the it appears that the total impacts from emissions and energy consumption are lower for both the automotive and industrial application in all the scenarios presented. This may in turn conclude that coconut residues utilization for power generation used during the biodiesel production should be equipped with proper instrumentation so as not to increase some of the air emissions. In this case, coconut biodiesel is really a potential alternative fuel.

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[13] ISO 14042 (2000a). Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment. International Organization for Standardization, Geneva.

[14] Vignes, R. P. (1999). Limited Life Cycle Analysis: A Tool for Environmental Decision-Making Toolbox. Strategic Environmental Management 1: 297–332.

[15] Stoglehner, Gernot (2002). Ecological Footprint – a tool for assessing sustainable energy supplies. Journal of Cleaner Production 11 (2003) 267 – 277.

[16] ISO 14043 (2000b). Environmental Management – Life Cycle Assessment – Life Cycle Interpretation. International Organization for Standardization, Geneva.

SUMMARY OF RESULTS AND CONCLUSION

Using both the automotive and industrial boiler applications in determining the total impacts of both coconut biodiesel and conventional diesel, we can observe the following:

- Total emissions of biodiesel and diesel appear approximately the same for both scenario 1 and 3. Meanwhile, for scenario 2 and 4, biodiesel has approximately 15% to 60% reduction on total emissions as compared to diesel. Global emissions such as CO_2 showed 60 to 100% reduction upon the use of coconut biodiesel. Local emissions such as NOx, SOx, PM_{10} and N_2O show as high as 60% reduction if there is no coproduct allocation. Table 2 shows the summary of scenario results.

Table 2 **Summary of Emission Reductions on Four Scenarios**

	SCENARIO 1 (AUTOMOTIVE W/ COPRODUCT UTILIZATION)	**SCENARIO 2 (AUTOMOTIVE W/O COPRODUCT UTILIZATION)**	**SCENARIO 3 (INDUSTRIAL BOILER USE W/ COPRODUCT UTILIZATION)**	**SCENARIO 4 (INDUSTRIAL BOILER USE W/ COPRODUCT UTILIZATION)**
VOC	-60.19%	-95.79%	-26.99%	-42.63%
CO	25.69%	-62.78%	4.31%	-13.28%
NOx	29.69%	-42.33%	4.95%	-9.01%
PM10	359.62%	-52.30%	21.90%	-4.26%
SOx	-49.06%	-57.65%	-19.24%	-22.50%
CH4	-83.17%	-99.31%	-54.43%	-64.93%
N2O	746.34%	-34.62%	25.54%	-2.19%
CO2	-100.00%	-59.38%	-100.00%	-59.38%

Legend: (-) = Percentage lower than diesel
(+) = Percentage higher than diesel

- Total energy consumption impacts do not change with respect to the coconut residues utilization scenarios. Moreover, the energy required to produce coconut biodiesel is still lower compared to conventional diesel even if there is coproduct allocation. This may be due to the nature of production of conventional diesel. Biodiesel has approximately 96% reduction in total energy impacts based from ecological footprint in all scenarios presented. In terms of the coconut residues utilization, both the automotive transport and industrial boiler applications show an increase in footprint values equal to 1.18% and 2.71% respectively. Meanwhile, for diesel life cycle, both for automotive transport and industrial boiler application, values remain constant equal to a footprint of 215.36 and 108.65 m sq. - a / MJ, respectively. Table 3 shows the summary of scenario results for total energy consumption impact.

Table 3 **Summary of Scenario Results for Total Energy Consumption Impact**

(m sq. - a / MJ)	**Scenario 1 (Automotive w/ Coproduct Utilization)**	**Scenario 2 (Automotive w/o Coproduct Utilization)**	**Scenario 3 (Industrial Boiler Use w/ Coproduct Utilization)**	**Scenario 4 (Industrial Boiler Use w/o Coproduct Utilization)**
Biodiesel	8.54	8.44	3.79	3.69
Diesel	215.36	215.36	108.65	108.65

MODEL VALIDATION

The results of the model using the critical volumes method and the ecological footprint measure were compared to other standard LCA models and methodology such as the Environmental Design of Industrial Products (EDIP), Framework for Responsible Environmental Decision-making (FRED)[17] and supply horizon. Figures 5 and 6 shows a sample EDIP and FRED graphical results.

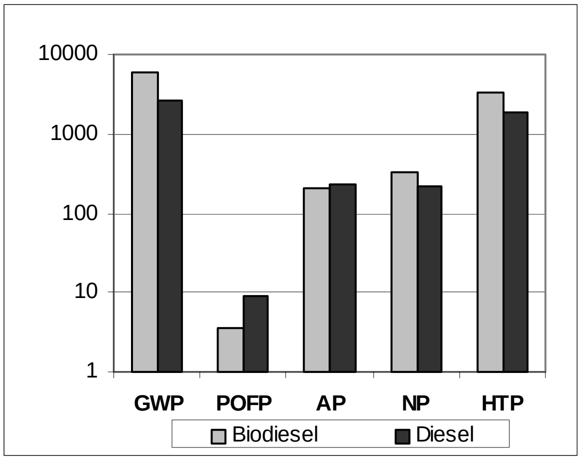

Figure 5 **EDIP Scenario 1 (Automotive w/ Coproduct Utilization)**

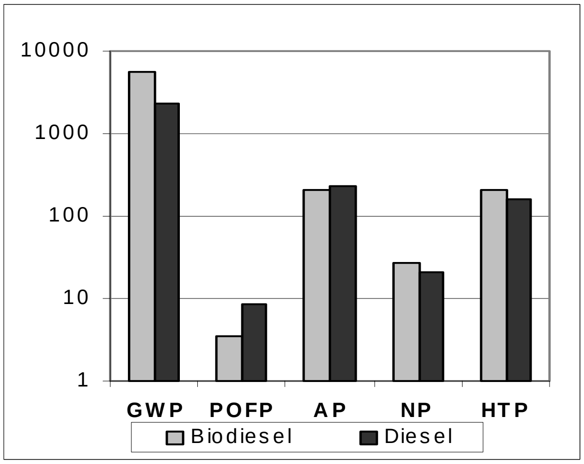

Figure 6 **FRED Scenario 1 (Automotive w/ Coproduct Utilization)**

Results of the comparisons made showed that other methods also have the same behavior of assessment as the critical volumes method. Environmental impacts of the coconut biodiesel appear high for scenarios where the coconut residues are utilized for power cogeneration. These may be due to the upstream emissions caused by using these residues. Although these methods give almost the same assessment as the critical volumes, results are not expressed into a single value. Impact categories should be ranked using weighting factors to arrive at a single result. These weights are user decisions and may change depending on the priority of the user. This is the great advantage of the critical volumes method over the other. With the use of the limits set by the government, we can arrive on a total environmental impact that can be evaluated easily. In terms of the energy use, ecological footprint is the most practical and applicable methodology since it can provide an assessment for both renewable and non-renewable resources.

Finally, comparing the results of two studies having similar conditions was also employed for additional validation of the model results. The following studies presented below are the results of previous LCA studies, which in some way have generally accepted results.

- ***Tan, Culaba, Purvis (2003)***[18] - In this paper, carbon dioxide inventory implications of coconut biodiesel in the Philippines are assessed. Results show approximately 80% reduction in

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[17] Science Applications International Corporation, et al (2000). Framework for Responsible Environmental Decision-Making (FRED): Using Life Cycle Assessment to Evaluate Preferability of Products. US-EPA.

[18] Tan, R., Culaba, A. and Purvis, M. (2003). Carbon balance Implications of Coconut Biodiesel utilization in the Philippine Automotive Transport Sector. Biomass and Bioenergy 2003.10.002.

CO_2 emissions, when residues are used to meet the heat requirement of the BD plant. An approximately 90% reduction was observed when residues are used to meet the energy requirement of the BD plant. Finally, approximately 110% reduction was observed when the excess power was exported. These results are in parallel to the results obtained from MEICOD v1.0.

- ***Sheehan et. al., (1998)***[19] **-** A comparative full life cycle assessment of diesel and soybean-derived biodiesel was conducted by the National Renewable Energy Laboratory (NREL) of the US Department of Energy. Results show that the use of 100% biodiesel or B100 in urban buses results in substantial reductions in life cycle emissions of total particulate matter, carbon monoxide and sulfur oxides (32%, 35% and 8% reductions, respectively, relative to petroleum diesel's life cycle). Substituting B100 for petroleum diesel in buses reduces the life cycle consumption of petroleum by 95%. The results are in qualitative agreement with the model outputs for coconut biodiesel input conditions. This is one of the most authoritative references for comparative LCA of diesel and biodiesel (Gerpen, 2000).

- ***Stoglehner (2003)***[20] **-** The model developed by Stoglehner calculates the footprint of energy supplies such as coal, petroleum, natural gas and rapeseed methyl ester. The footprint calculated in the model developed in this study and its relationship with other energy resource footprints are in conjunction with the one developed by Stoglehner.

- ***Komiyama et. al. (2001)***[21] **-** This study published in fuel journal is an assessment of energy systems by using biomass plantations. Biomass applications include conversion processes producing oil, ethanol, methanol and hydrogen. Results of the study show that reductions in CO_2 emissions can be observed by using these renewable fuels.

- ***Shaheed and Swain (1999)***[22] **-** This study analyzes the combustion advantages of using coconut methyl ester or CME in a tropical country. It concludes that CME has several engine benefits when used mostly in tropical countries where the ambient temperature is above 25°C. This in turn, supports the Philippine effort in using CME as an alternative fuel and as additive.

- ***Wang and Huang (1999)***[23] **-** This study was conducted at Argonne National Laboratory using GREETv1.5a. Assessments were made for both conservative and long-term vehicle

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[19] Sheehan, J., Camobreco, V., Duffield, J., Graboski, M. and Shapouri, H. (1998). Final Report: Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. NREL/SR-580-24089 UC Category 1503.

[20] Stoglehner, Gernot (2002). Ecological Footprint – a tool for assessing sustainable energy supplies. Journal of Cleaner Production 11 (2003) 267 – 277.

[21] Komiyama, H., Mitsumori, T., Yamaji, K. and Yamada, K. (2001). Assessment of Energy Systems by Using Biomass Plantation. Fuel 80: 707 – 715.

[22] Shaheed, A. and Swain, E. (1999). Combustion Analysis of Coconut Oil and Its Methyl Esters in a Diesel Engine. Journal of Power & Energy 213: 417 – 425.

[23] Wang, M. (1999). GREET 1.5a – Transportation Fuel Cycle Model. Final Report ANL/ESD-39, Argonne National Laboratory, USA.

performance assumptions, but no attempt was made to go beyond inventory analysis. Results for soybean-derived biodiesel shows an aggregate impact better than conventional diesel.

Validation of the model outputs based from the previous LCA studies showed that the generated results are reliable and shows realistic values.

RECOMMENDATIONS

The following recommendations and improvement of the study are suggested:

- Options for coconut biodiesel and diesel fuel mixtures in the model.
- Data uncertainty analysis using Monte Carlo simulation or fuzzy logic.
- Actual measurement of emissions from biodiesel- and diesel-fired boilers and automotive engines.

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