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CHBE 484 / SEEDS project: Comparison of three sources of biodiesel based on a Life Cycle Analysis

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Executive summary

This report aims at presenting the context, the methodology and the results of the comparison of three sources of biodiesel based on a Life Cycle Analysis (LCA). This SEEDS project has been assigned by the UBC Sustainability office in the context of the CHBE 484 course offered by Dr. Xiaotao Bi at the University of British Columbia.

The scope of this study is to assess the CO_2-equivalent emissions linked to the biodiesel utilized on UBC Campus on a LCA basis. The final purpose is to find out if reusing waste vegetable oil collected from UBC campus restaurants could be an environmental-friendly feedstock for biodiesel production and fuelling. To do so, this scenario is compared to two other possibilities: utilization of biodiesel from Canadian canola and utilization of biodiesel from American soybeans. The economical aspect has not been studied as little information was available and too many assumptions would have been taken.

To perform the LCA, the principle stages of the life of the product (biodiesel) have been considered to quantify the emissions of CO_2-eq: production of fertilizers, crop cultivation, oil production, transportation, etc (when relevant). Some life steps have not been considered; those are stages common to the three scenarios and imply identical emissions (emissions from combustion, emissions from biodiesel production…).

Due to the tremendous amount of data needed, the LCA has been carried out with the help of a software developed in the United States but now utilized by the Natural Resources Canada federal agency; this software is called GHGenius. Some explanations about this program are given in this report.

The results from the simulation confirm that the utilization of yellow grease (used vegetable oil) for biodiesel production creates fewer environmental impacts than the two other scenarios (canola and soybean). This is mainly because the life stages emitting more pollutants are linked to crop production and cultivation; waste oil biodiesel is indeed not concerned by these steps. Other interpretations are given in this document.

Waste oil reuse in biodiesel production thus appears to be a good solution to reduce the overall emissions of the campus and to "close a loop" by using a waste as a feedstock for another process.

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Introduction

For many years now, the University of British Columbia has been one of Canada's leading universities in terms of climate action and energy management. Amongst these steps taken toward sustainability, the reduction and further the "neutralization" of Green House Gas (GHG) emissions is one of the main current concerns on the campus. Because the university is required to be "carbon-neutral" by the year 2010, the UBC Sustainability Office has been trying to involve the whole UBC community in actions, plans and projects aiming at decreasing these atmospheric emissions.

As part of this program, the utilization of biodiesel has been recommended for more than two years and many vehicles of UBC fleet now run with a blend of "classic" diesel and biodiesel, thus contributing to the decrease in carbon dioxide (CO_2) equivalent emissions. However, biodiesel can be produced in different ways, from various raw materials and the overall emissions of GHG can differ between these sources according to a Life Cycle Analysis (LCA).

The scope of this term paper, product of the collaboration between students, instructors, UBC SEEDS office and UBC plant operations, is to analyze and compare the GHG emissions of three different types of biodiesel based on a LCA: biodiesel from canola oil produced in Alberta, biodiesel from soybean oil produced in Iowa and biodiesel from used vegetable oil collected in UBC campus restaurants. The final purpose of this study is to find whether using campus waste oil as a biofuel feedstock would be environmentally friendly and thus give UBC management a tool to help make this decision.

In the present report, the basic characteristics of a LCA are first presented. A second part concerns the software that has been utilized to calculate the emissions from the various sources of biodiesel: GHGenius. Then, in a third part, more details are given concerning the data that has been considered. Finally, the results and a brief analysis of the comparison will be given before a conclusion on this study.

1. Life Cycle Analysis

When comparing different solutions from economical or environmental points of view, LCA is a tool that is often utilized to give a more accurate perception of the problem. Indeed, a simplified analysis of product costs or emissions can sometimes lead to a misinterpretation and create erroneous decisions: this is particularly the case when considering fuel emissions. As an example, hydrogen fuel cell vehicles have in many cases been characterized as "zero-emission" cars. If a hydrogen-operating engine doesn't typically emit GHG (assuming steam is not a GHG), this is not the case for life stages like the production of the hydrogen or the recycling of the engine. This makes LCA a useful and comprehensive tool which has been used in this term paper to provide a reliable means of comparison.

1.1. General definition of a LCA

Life Cycle Assessment is a "well-to-wheels" approach utilized to assess industrial systems. This iterative method usually starts with the gathering of raw materials from the earth to create the product and ends when all materials have been returned to the earth. LCA evaluates all the main stages between these two "extremities" of the products life, LCA evaluates all main stages by considering they are entirely independent (one operation leads to the next one). In this manner, LCA provides a more comprehensive and accurate conclusion concerning the ecological and environmental aspects of a product/process (1) (2) (3).

1.2. Main steps of a LCA

Three major stages have to be considered when performing a LCA (4):

- Compilation of relevant and up-to-date energy/material inputs and environmental releases. These data often come from various researches and analysis.
- Evaluation of the potential environmental impacts which are associated with these inputs and releases.
- Interpretation of the results in order to make informed decisions.

These different steps have been followed during this term project and will be explained in this report.

1.3. Cycles of the life of a product/process

When performing a LCA on a product/process, the major activities during the product's life span have to be taken into account. Although this usually depends on the kind of product/process considered, the following figure gives a simplified illustration of the "classic" possible life cycle stages and input/output measured:

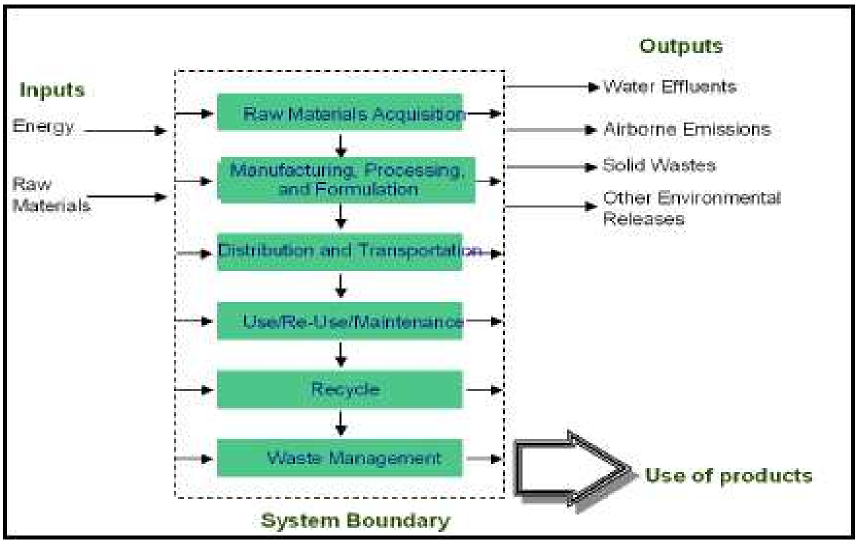

Figure 1: Life cycle stages of a product (source: (5))

Depending on the scope of the LCA and the boundaries chosen for the studied system, this diagram can be simplified or even much more complex.

1.4. Limitations and LCA applied to our subject

Therefore, it clearly appears that LCA is the best tool to compare, in our case, the GHG emissions from different sources of biodiesel (principally because they have a similar functional unit i.e. fuelling the same vehicle).
If LCA is to be an effective tool to compare the environmental impacts of different products, it requires a large amount of updated data for every considered stage of each biofuel life. Because this data comes from diverse sources, not always clearly identified (most of them are national and federal laboratories but some are private companies or university research departments), this task would have been too complex and physically impossible concerning this project, given the short time period assigned.

To obtain a comparison as complete as possible, using actualized data and allowing more informed decisions at the end of LCA, various LCA software have been created in North America and are freely available throughout the Internet. Amongst these models, two are widely utilized in Canada and the USA: GREET (for Greenhouse gases, Regulated Emission and Energy used in Transportation), and GHGenius.

As part of this project, the later one has been chosen to perform the three LCAs and is presented in part 2 of this report.

2. GHGenius software

One of the main steps of this term project was to determine which tool would be used for the LCA of the three biodiesels. Indeed, many programs exist for performing a LCA of biodiesel but it was necessary to select the most suitable one. For instance the, flexibility, simplicity, and how complete the model is, in term of inputs and outputs were important parameters, were essential to take into account when choosing the LCA tool. Considering all these parameters, GHGenius has been selected to perform this LCA.

2.1 What is GHGenius?

GHGenius is an Excel spreadsheet-based software which has been developed for Natural Resources Canada. It focuses on Life Cycle Analysis (LCA) of fuels for transportation application (2) (3).
Dr. Mark Delucchi is at the origin of this software.

Between 1987 and 1993, he first made the Lifecycle Emissions Model (LEM) that was a spreadsheet with which it was possible to add input data and get emissions of GHG and other gaseous pollutants for many alternative fuels for the USA transportation sector.

Between 1998 and 1999, Dr. Delucchi updated LEM with Canadian data on request for Natural Resources Canada. This version of the software has been the basis used for GHGenius development. Between 1999 and 2007, the software has been utilized in many studies for Governments and Industry. GHGenius data were updated and revised little by little in order to run the software for both USA and Canada, and later Mexico. In 2001, Levelton and Delucchi revised GHGenius so that projections in the future (till 2050) become possible, as well as the possibility to perform more detailed regional analysis for Canada and the USA. In 2002, the production of biodiesel from vegetable oils, tallow and yellow grease was added to the software, and the production of biodiesel from marine oils was included in 2004.

Thus, GHGenius has many alternative fuel pathways (e.g. ethanol from corn or wheat, ethanol from lignocellulosic feedstocks, methanol for fuel cell vehicles, various methods of producing hydrogen for fuel cell vehicles, biodiesel and ethanol blended diesel fuel and mixed alcohol) applied to traditional light and heavy-duty vehicles.

GHGenius gives a detailed output for all contaminants as well as an analysis for the lifecycle cost of greenhouse gas emission reductions.

2.2 What are GHGenius input, output, and how does it work?

In GHGenius, inputs are already set in the spreadsheets. Most of them are already chosen as default values but much of the data needs to be modified by the user in order to make the software fit with the particular scenario that is considered.

Concerning the USA, data comes from many sources but mainly the US DOE Energy Information Administration for historical data and future projections for processes (e.g. electric power, crude oil, refined petroleum products, natural gas and coal production), or US Census reports. For Canada, these data mainly come from Statistics Canada, Natural Resources Canada, Environment Canada and the National Energy Board (information on the production of power, crude oil, refined petroleum products, natural gas and coal production), and Industry associations (e.g. Canadian Association of Petroleum Producers (CAPP), Canadian Gas Association (CGA), etc.). When precise data were not available, less accurate values have been considered such as industry average measures, actual operating plant data, engineering design data, data from pilot plants, engineering simulations, and scientific experiments (depending on the availability of the most accurate data source) (4) (6).

***Remark**: For non-energy related process emissions, emission factors come from US EPA AP-42, Environment Canada model Mobile6.2C. Relative emission factors (used for alternative fuels) are based on analysis performed by the US EPA and in other cases from an assessment of the available literature.*

Some of the inputs are going to be detailed in the part 3 of this report.

In brief, GHGenius has data for all of the processes available in the model. Some of these data can be easily modified by the user in the input sheet in order to have the possibility to customize the LCA when required. Changes in specific steps of the life cycle can also be done. However, all these possible changes need to be carried out carefully in order to get coherent results.

Finally, once all the inputs have been assigned, GHGenius can be run; it calculates emissions from each fuel cycle taken into account in the software, as detailed in section 3 of this report. A large variety of outputs are given but the most interesting ones for this term paper are the pollutant emissions for each stage of the fuel cycle and each type of fuel.

2.3 Why choose GHGenius?

In March 2008, a study determined that GHGenius and GREET were the most capable models of conducting a LCA of biodiesel among nine potential ones that have been identified as those offering the best options for biodiesel LCA (5). The conclusion of this report was that GHGenius was more flexible and complete than GREET, and thus more suitable for biodiesel LCA.
Considering the differences, advantages and drawbacks of the two software, we have decided to choose GHGenius as a basis for this LCA.

Indeed GHGenius has many advantages:

- GHGenius includes the three biodiesel pathways which were studied during this term paper (i.e. biodiesel from soybeans, canola, and yellow grease), whereas GREET only has biodiesel from soybeans.
- GREET is only suitable for the USA whereas GHGenius can be run for both Canada and the USA.

To conclude, GHGenius has been chosen to perform this LCA because, it includes the three biodiesel feedstock's that need to be studied, and allows the user to adapt the LCA without compromising the quality of the results. Thus, GHGenius is complete and flexible enough in order to perform this LCA.

3. Configuration studied

In this part of the report, the three scenarios that have been studied are detailed and the corresponding software inputs are given. In a second part, the LCA steps considered by GHGenius during modeling are presented and some important data utilized by the software are displayed in order to better understand the results of the test.

3.1. Three types of biodiesel, three scenarios

In order to perform the LCA, three scenarios have been thoroughly defined to try and represent UBC's choices when selecting different kinds of biodiesel sources.

We were tasked to compare three biodiesel sources capable of meeting UBC's demand of 15000L/year and that met ASTM standards for fuel quality. The following configurations have been considered and the locations are displayed on figure 2:

- Canola oil as a feed stock sourced from Canada
- Soy oil as a feed stock sourced from the USA
- Waste vegetable as a oil feed stock sourced from Vancouver

Three companies meeting these outlines were found using various sources:

- Lee Ferrari from UBC plant operations provided us with some details about West Coast Reduction Ltd (7), and the Canadian Bioenergy Corporation (8).
- Columbia Bio-Energy was found using a biodiesel network webpage (9).

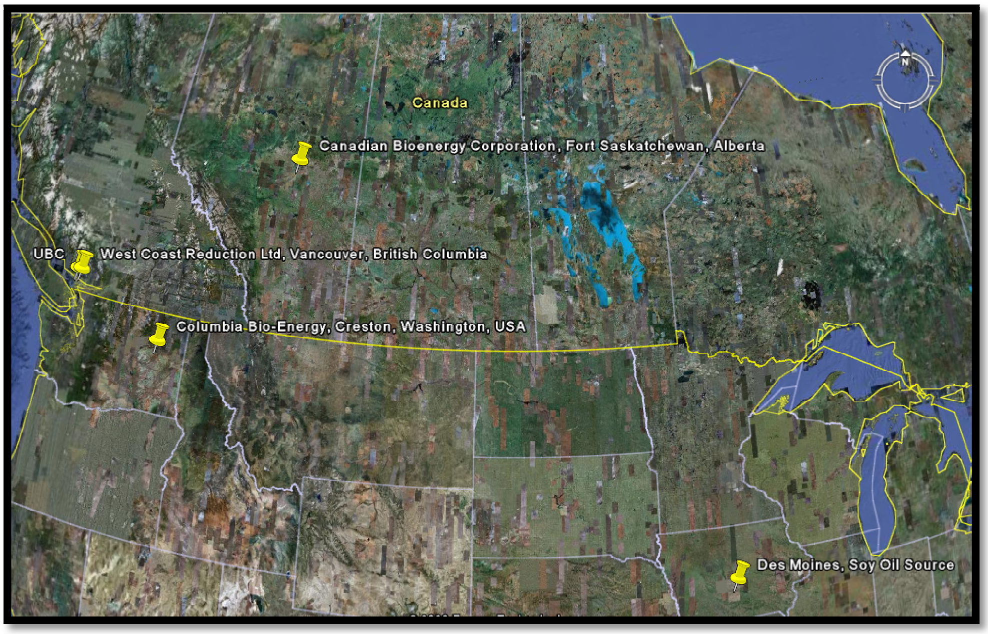

Figure 2: A display of the locations (source: (10))

3.1.1. Scenario 1: Canola oil from Canada – Canadian Bioenergy Corporation

Canadian Bioenergy Corporation is Western Canada's leading supplier of biodiesel; they use Canola as a feedstock and process 225 million litres per year meeting BQ-9000 standards (on top of ASTM). Their biodiesel plant is located in Fort Saskatchewan, Alberta. The facility is adjacent to a Bungee oilseed crushing plant, from which their Canola oil is sourced (11), as illustrated by figure 3. The site is rail serviced and the oil would be transported by train to their Vancouver distribution centre located at 221 Esplanade W North Vancouver, V7M 3J3, Canada.

The distance from the farm to the refinery is judged to be 20km from looking at Google Earth and assessing the amount of farmland in the area. The distance travelled by train is also measured on Google Earth by measuring the line of the tracks to Vancouver. This method is very basic and will have some error associated with it.

Figure 3: The Plant and Crushing facilities, with rail link (source: (10))

The distance from the Vancouver facility to UBC has been calculated via Google map (figure 4).

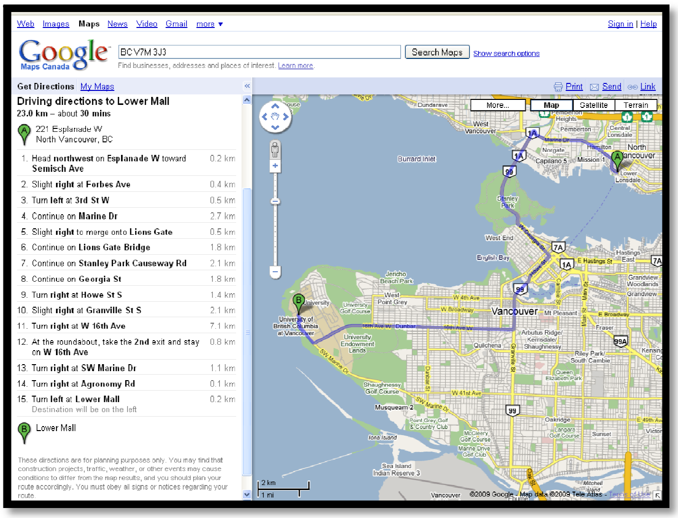

Figure 4: Distribution itinerary to UBC (source: (12))

A summary of the different distances considered is given by the following table (table 1):

Table 1: Distance inputs in GHGenius for scenario #1

Itinerary	Distance (in km)	Transportation type
From farm to refinery	25	Truck
From Fort Saskatchewan to Vancouver (via Edmonton)	1150	Train
Distribution to UBC	23	Truck

3.1.2. Scenario 2: Soy oil from United States – Columbia Bio-energy

Columbia Bio-Energy LLC is Washington's largest producer of biodiesel with a current production capacity of 35 million litres per year. They currently import soy oil as a feedstock (13) (14). This is assumed to come from Iowa, as this State is the largest of soy oil. Des Moines was taken to be the location that the oil would be transported from as it is the commercial centre for Iowa:

- The Soy is farmed and crushed in Iowa to create soy oil;
- The oil is then taken by train to Creston, WA, where the company's biodiesel plant is located.
- After processing the biodiesel would be transported by train to Vancouver.

It should be noted that Columbia Bio-Energy does not currently distribute in Canada, therefore special provision would have to be made for this. It should also be noted that Columbia Bio-Energy is looking to switch its feed stock from soy oil, opting to produce biodiesel from locally grown Canola as well as recycled oils, in the near future.

Again the distances travelled by train are measured on Google Earth by measuring the line of the tracks. This method is very basic and will have some error associated with it.

Remark: Columbia Bio-Energy was the nearest producer of Soy Biodiesel that could be found to UBC, but there are many other options available when importing biodiesel from the US. Lists of suppliers can be found on (13).

A summary of the different distances considered is given by the following table (table 2):

Table 2: Distance inputs in GHGenius for scenario #2

Itinerary	Distance (in km)	Transportation type
From farm to Des Moines (Iowa)	100	Truck
From Des Moines to Creston (Washington)	2700	Train
Railroad to Refinery (in Creston)	5	Truck
Refinery (Creston) to Vancouver	600	Train
Distribution to UBC	22	Truck

3.1.3. Scenario 3: Yellow grease oil from Vancouver – West Coast Reduction

West Coast Reduction Ltd is a rendering company based in Western Canada that has recently started supplying biodiesel. They currently distribute fuel purchased from United Petroleum, but are in the process of creating their own Biodiesel plant to convert yellow grease, which they already handle as part of their rendering services (especially to UBC). The plant will reportedly be located with their Vancouver facilities at 105 North Commercial Drive, Vancouver, V5L 4V7 and will have a capacity of 50 million litres per year (15).It should also be noted that West Coast's fleet of vehicles runs on biodiesel, which will lower their environmental effects during distribution (16).

It is assumed that the waste oils sourced from the Lower Mainland area will be enough to meet plant capacity, and oil will not have to be transported by train from their other facilities near Edmonton and Calgary, in Alberta. We were unable to gain more information on this from West Coast, so the collection distance was taken as an average distance of travel for the Lower Mainland area, to their processing plant (figure 5).

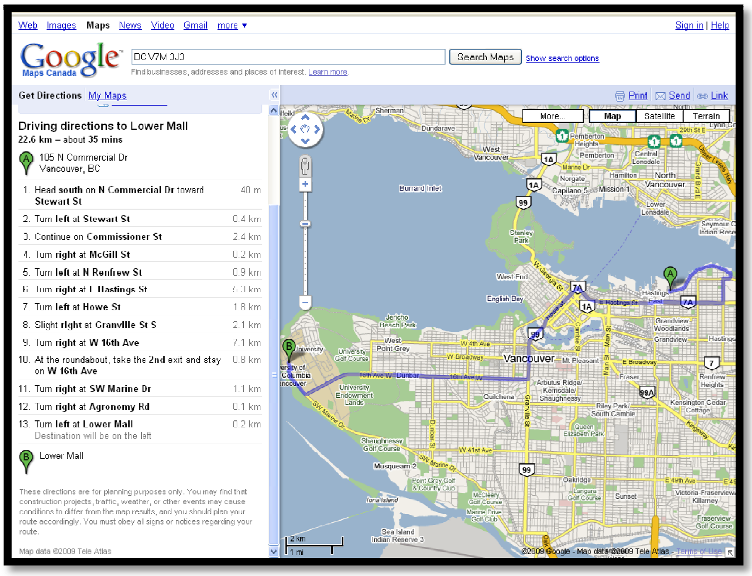

Figure 5: Distribution by biodiesel fuelled truck to UBC (source: (12))

A summary of the different distances considered is given by the following table (table 3):

Table 3: Distance inputs in GHGenius for scenario #3

Itinerary	Distance (in km)	Transportation type
Used oil collection (Lower Mainland, Vancouver)	25	Truck
Distribution to UBC	22	Truck

3.2. LCA steps considered in GHGenius

3.2.1. Overview

As previously stated in section 1 of this report, carrying out an LCA identifies each stage in the life of the product studied. As software specialized in LCA for vehicle fuels comparison, GHGenius is able to calculate the emissions linked to different stages of the life of the fuel.

These stages are usually separated into two components: “well to tank” and “tank to wheel”. They are represented in the figure in Appendix 1.

3.2.2. Assumptions and simplification of the model

However, because GHGenius is a very complete model and thus quite complicated to run, some assumptions had to be made in order to simplify this fuel comparison and restrain the number of stages to be studied. The following major assumptions have been considered:

- The emissions will be considered for heavy duty vehicles, combined buses and trucks (in the software). This does not change the results of the comparison.
- The software will be run for 100% Soybean biodiesel, 100% Canola biodiesel and 100% Yellow Grease biodiesel (no blend). Indeed, once the three types of biomass oils have been produced, the production of biodiesel is assumed to be identical in the three cases (mix of bio oil with methanol and

diesel); the emissions are thus the same. It is also a way to better underline the differences in emissions for the three scenarios.

- This study will only focus on the "well to tank" stages. Indeed, without any precise information about engines emissions, it can be assumed that these emissions are approximately equal, whatever biodiesel is used, especially with a blend 80/20 (80% normal diesel, 20% biomass fuel).
- The emissions from other life cycle stages won't be considered as well: fuel dispensing, vehicle assembly and transport and materials utilized for these vehicles are supposed to be completely identical (in respect of the functional unit principle).

It is important to notice that these assumptions won't affect the results of this study for the two following points:

- The stages removed implied identical emissions for the three sources of biodiesel.
- Therefore, relative results are sufficient. In other words, the final results displayed in section 4 of this report are not the total emissions for each biofuel, but the summation of the stages emissions where emissions are different.

3.3. Examples of GHGenius data

This part of the report aims to present some examples of important default data utilized by GHGenius for the modelling of the emissions. There are three main categories of data:

- Technical and scientific data linked to farming activity, biodiesel production processes…
- Emission factors linked to a particular process, a specific fuel utilization, etc.
- Geographical and economical information (energy repartition, vehicle consumption…)

For more information about these data, one can refer to the various GHGenius reports listed in the references of this report (17) (6) (3) (2) (4) (5).

3.3.1. Energy data

The following basic data are linked to energy utilization throughout the calculations in GHGenius models.

Table 4: Efficiencies of different sources of energy (for the year 2009)

Region	Coal	Oil	Gas Boiler	Gas Turbine	Nuclear	Wind	Other Carbon	Biomass	Hydro	ELECTRICITY DISTRIBUTION
Canada West	0,34	0,35	0,36	0,54	n.a.	1,00	0,38	0,46	n.a.	0,92
US Central	0,33	0,28	0,41	0,41	n.a.	1,00	0,41	0,26	n.a.	0,93

Table 5: Repartition of different sources of energy for electricity production (for the year 2009)

Region	Coal	Oil	Gas Boiler	Gas Turbine	Nuclear	Wind	Other Carbon	Biomass	Hydro	Other
Canada West	0,29	0,00	0,02	0,14	0,00	0,02	0,00	0,03	0,50	0,00
US Central	0,65	0,00	0,10	0,06	0,15	0,01	0,00	0,01	0,01	0,00

These data are then utilized in two different ways:

- Calculate the emissions due to electricity (for transportation and/or for direct use in a process for instance),
- Calculate the emissions due to each energy source (for direct use in a process mainly).

Emission tables for the above sources are given in Appendix 2 of this report.

3.3.2. Transportation data

The following basic data are linked to transportation of fuels and feedstock throughout the calculations in GHGenius models (source: (4)).

Table 6: Energy for Rail Transportation

	Energy Consumed
	kJ/tonne-km
Solid bulk in unit trains	181
Solid bulk	336
Liquid bulk	336
Low pressure gas (LPG, DME)	370
Liquid hydrogen	1,680
Compressed hydrogen	17,140

Table 7: Energy and GHG Emissions for Truck Transportation

	Energy Consumed	GHG Emissions
	kJ/tonne-km	g CO_2 eq/tonne-km
Crude oil	1,374	182.3
Solid bulk	1,591	211.0
Liquid bulk	1,409	186.9
Low pressure gas (LPG, DME)	1,550	205.6
Liquid hydrogen	7,047	934.7
Compressed hydrogen	71,879	9,534.2

***Remark:** in our case, only solid and liquid bulks are considered. The emissions are then calculated depending on electricity energy sources.*

3.3.3. Fertilizer production data

The energy requirements and emission performance for each type of fertilizer are presented in the following tables. They usually include raw materials mining but also the production, the mixing and the transportation of these final products (average values Canada) (source: (4)).

Table 8: Energy and GHG Emissions for Nitrogen fertilizer production

	Energy Requirements	Emissions
	kJ/kg nitrogen	g CO_2 eq/kg nitrogen
Manufacture	44,016	2,616
Fertilizer mixing	520	31
Fertilizer transport	728	43
Total	45,265	2,690

Table 9: Energy and GHG Emissions for Potassium fertilizer production

	Energy Requirements	Emissions
	kJ/kg potassium	g CO_2 eq/kg potassium
Mining	2,143	126
Mineral transport	378	22
Manufacture	n.a.	n.a.
Fertilizer mixing	903	53
Fertilizer transport	see mineral	see mineral
Total	3,423	202

Table 10: Energy and GHG Emissions for Phosphorus fertilizer production

	Energy Requirements	Emissions
	kJ/kg potassium	g CO_2 eq/kg potassium
Mining	828	65
Mineral transport	717	56
Manufacture	4,927	384
Fertilizer mixing	184	14
Fertilizer transport	760	59
Total	7,415	579

3.3.4. Feedstock production data

This part gathers the basic data about the feedstock production for each scenario (source: (4)).

Table 11: Typical values utilized for feedstock production

Parameter	Canola crop	Soybean crop	Vegetable waste oil
Crop yield	1.29 ton/ha	2.42 ton/ha	n/a
Seed requirements	5.2 kg/ton	41.67 kg/ha	n/a
Nitrogen fertilizer	46 kg/ton	3.33 kg/ton	n/a
Phosphorous fertilizer	22 kg/ton	13.33 kg/ton	n/a
Potassium fertilizer	10 kg/ton	23.33 kg/ton	n/a
Sulphur fertilizer	8 kg/ton	1.67 kg/ton	n/a
Pesticide	1.4 kg/ton	0.52 kg/ton	n/a
Fuel requirement	35 L/ton	14 L/ton	n/a

3.3.5. Oil production data

This part gathers the basic data about the oil production from feedstock and the processes considered for each scenario.

***Remark:** there is no possibility to choose the process conducting to oil production in GHGenius. The most utilized process is the one included in the software, as well as average Canadian values for mass balances and energy requirements.*

- **Canola and Soybean oils**

The process of oil production from canola or soybean crop is illustrated and simplified in the following flow diagram:

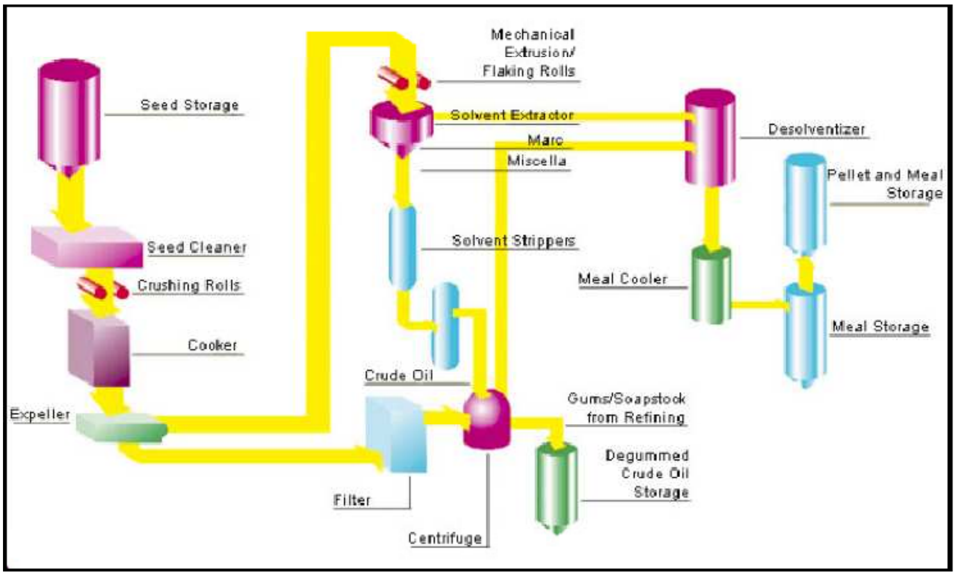

Figure 6: Canola and Soybean typical crushing process (source: (4))

The inputs and energy requirements considered in GHGenius are the following (source: (4)).

Table 12: Canola Crushing Model inputs

	Per tonne Oilseed	Per litre Oil
Electricity	45 kWh/tonne	0.08 kWh
Natural Gas	844,000 kJ/tonne	50 L
Hexane	1.9 l/tonne	0.004

Table 13: Soybean Crushing Model inputs

	US Average	
Electricity	0.35 kWh/l	68 kWh/tonne
Natural Gas	156 L/litre	812,000 kJ/tonne
Hexane	0.019 L/L	0.98 USG/tonne

- **<u>Yellow grease (from Waste Vegetable oil)</u>**

The process of oil production based on waste vegetable oil (the final product is called yellow grease) is illustrated and simplified in the following flow diagram:

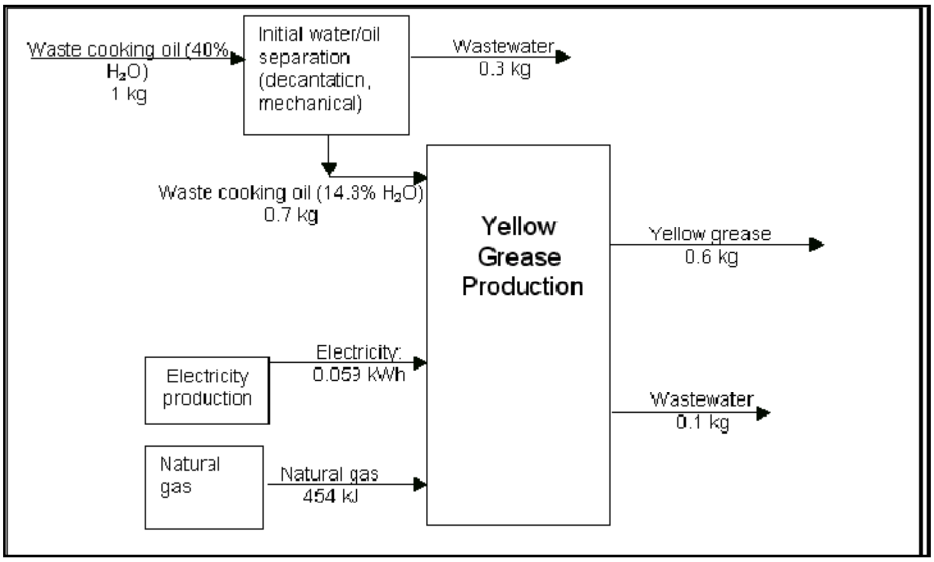

Figure 7: Yellow grease production process (source: (4))

The inputs and energy requirements considered in GHGenius are the following (source: (4)).

Table 14: Yellow grease process requirements

	Per kg Yellow Grease	Per litre of Yellow Grease
Electricity	0.099 kWh	0.09 kWh
Natural gas	0.757 MJ	17.7 L

3.4. GHGenius: from data to results

As already enounced in this report, GHGenius is a complete but complex model. However, a simplified method of GHGenius model procedure applied to our case could be written as following:

- Step 1: calculus of a volume of biodiesel required from both vehicle consumption and a given number of kilometres over the life of the selected vehicle (automatically set in the software).
- Step 2: in function of this number and depending on emission data for each stage (cf. example of data in section 3.3.), calculation of the amount of gases emitted for each life cycle step.
- Step 3: summation of all the emissions for each contaminant/output and/or expressed as an amount of CO_2 equivalent (via the use of Global Warming Potential associated to each contaminant, see section 4 for more details about GWP).
- Step 4: division of this total by the number of kilometres of step 1.

The results are thus given in terms of "g of contaminant per kilometre" and/or "g of CO_2 equivalent per kilometre". These results are explained more deeply in the next section of this report, and especially the ones obtained with the three sources of biodiesel.

Caution: *The above explanations just intend to give a simplistic view of GHGenius model. However, the software is one of the most complex existing LCA programs because of the variety of configurations and the extent of data that can be compiled. More information can be found in the various reports listed in references* (17) (6) (3) (2) (4) (5)*.*

4. Results of the LCA via GHGenius and interpretation

Various types of results (technical, economical, sensitivity analysis, etc) can be given by GHGenius. However, our concern in the context of this term paper is the emission of pollutants for our three scenarios. This part details these results.

4.1. "Raw" results

GHGenius directly gives the emissions in terms of gram per kilometre for each pollutant considered, each stage of the life-cycle and for each scenario. These results are summed up in the Appendix 3 and a comparison can be done via the table presented in Appendix 4.

***Remark**: "Negative" emissions appear for:*

- *The stage "Emissions displaced by co-products"; this is because co-products of the biodiesels (such as commercial oil, meals…) are considered to be credited for a part of the emissions associated with biodiesel production,*
- *The stage "Land use changes and cultivation" for CO_2 emission; this is because carbon dioxide fixation by plants during crop cultivation is considered and overcomes the emission of CO_2 during this stage.*

However, the comparison is not easy to make as a lot of pollutants are considered. Consequently, we are going to turn this data into environmental impacts, to make a comparison of effects clear.

4.2. Environmental Impacts: theory

Now that we have the emissions for each gaseous pollutant, we can calculate the Environmental Impacts (EI) associated to each biodiesel type:

- The main EI to be determined is the Global Warming Potential (GWP) that gathers the contribution of each contaminant to the global warming phenomenon.
- Because other adverse environmental effects could be induced, three other EI have been assessed:
    - the Smog Formation Impact (SFI) which represents the summation of each pollutant contribution to the local formation of smog,

  - the Acid Rain Impact (ARI) which represents the summation of each pollutant contribution to regional acid rain processes and,
  - the Ozone Depletion Impact (ODI) which represents the summation of each pollutant contribution to the global ozone depletion mechanism.
- In addition, the Human Toxicity Impact (HTI) has been determined by using the Threshold Limit Values (TLV) for each compound, to compare the possible health impact of each scenario.

To do so, the contribution factors (also called potential) for each EI and HTI and for each pollutant have to be considered. The next table (table 15) sums up this data:

Table 15: Contribution factors (potential) of each pollutant to EI and HTI

Pollutants	GWP	ODP	ARP	SFP	TLV (ppm)
CO_2	1				5000
CH_4	21			0.0020	1000
N_2O	310				50
CFCs + HFCs	4150[1]	0.5[2]			1000[3]
CO	1.57[6]				25
NO_x	40		0.7		3
VOC - Ozone weighted	2.965[4] [6]			0.0494[5]	800
SO_x	0		1		2
PM	0				0

[1] [2] According to GHGenius, the main CFC (ChloroFluoroCarbons) is CFC-12 and the main HFC (HydroFluoroCarbons) is HFC-134a. As the proportions are unknown, an average value has been calculated with the following values:

GWP(CFC-12) = 7100 and GWP(HFC-134a) = 1200 ; ODP(CFC-12) = 1 and ODP(HFC-134a) = 0.

[3] TLV(CFC-12) = 1000ppm but TLV for HFC-134a is not established yet, so 1000ppm has been chosen as default value.

[4][5] Average values have been taken by considering a mixture of 50% C_2H_6 and 50% C_3H_6. It is assumed that these compounds are the most frequent VOCs released when fuel is burned.

[4] It is assumed for CO, C_2H_6, C_3H_8 that once released into the atmosphere they will be oxidized to CO_2 and thus will play a role in GW impact. Indeed:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad \text{thus, we have} \quad GWP_{CO} = \frac{1 \times M_{wt}(CO_2)}{M_{wt}(CO)} \approx 1.57$$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O \quad \text{thus, we have} \quad GWP_{C_2H_6} = \frac{2 \times M_{wt}(CO_2)}{M_{wt}(C_2H_6)} \approx 2.93$$

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \quad \text{thus, we have} \quad GWP_{C_3H_8} = \frac{3 \times M_{wt}(CO_2)}{M_{wt}(C_3H_8)} = 3$$

Note: The other values for Environmental Impact potentials have been found in the course notes (1). TLV values have been found either in the course notes or in MSDS from OSHA website (1) (18).

***Remark #1**: Concerning smog formation, the Maximum Incremental Reactivities (MIR) are obtained for each pollutant from course notes* (1), *and SFP are then calculated by dividing by the MIR of the benchmark compound ethane C_2H_4.* $SFP_i = \frac{MIR_i}{MIR_{ethene}} = \frac{MIR_i}{7.4}$

***Remark #2**: The accuracy of the data in the previous table is not a major concern as our goal is to compare the three biodiesel. Indeed, an inaccurate value would only impact the three options in a way that will not affect the rankings, allowing a fair comparison.*

Then, for each pollutant, by multiplying the emissions E by the GWP (ARP, SFP or ODP respectively), we can get the different impacts on GW (AR, SF, or OD respectively). Finally, the sum of all pollutant contributions gives the total impact of the biodiesel for each environmental impact:

Table 16: Formula to calculate GW, AR, SF and OD (source: (1))

Global Warming	Acid Rain Formation	Smog Formation	Ozone Depletion
$EI_{GW} = \sum_i (GWP_i \times E_i)$	$EI_{AR} = \sum_i (ARP_i \times E_i)$	$EI_{SF} = \sum_i (SFP_i \times E_i)$	$EI_{OD} = \sum_i (ODP_i \times E_i)$

Moreover, the Human Toxicity of each scenario can be estimated by using the Threshold Limit Values (TLV) for each pollutant. Then total Human Toxicity Impact (HTI) can be calculated by applying the following formula: $HTI = \sum_i \left(\frac{E_i}{TLV_i}\right)$

4.3. Final results and interpretation

4.3.1. Final results

The final results are displayed in the following table (table 17) and graphs (figures 8 and 9).

Table 17: Total Impacts results

TOTAL IMPACTS (g/km)					
	GWI	**ODI**	**ARI**	**SFI**	**HTI**
CANOLA	432.47	0.00000964	5.35	0.02057	2.54
SOYBEAN	724.29	0.00001817	6.11	0.02503	2.95
WASTE COOKING OIL	-98.44	0.00000332	0.33	0.01723	0.14

***Remark:** again, these results have to be utilized in order to compare the three scenarios, considering the assumptions that have previously been evoked. For instance, even if the GWI of the waste cooking oil scenario is negative (no absolute meaning), comparison can still be made with the two other solutions.*

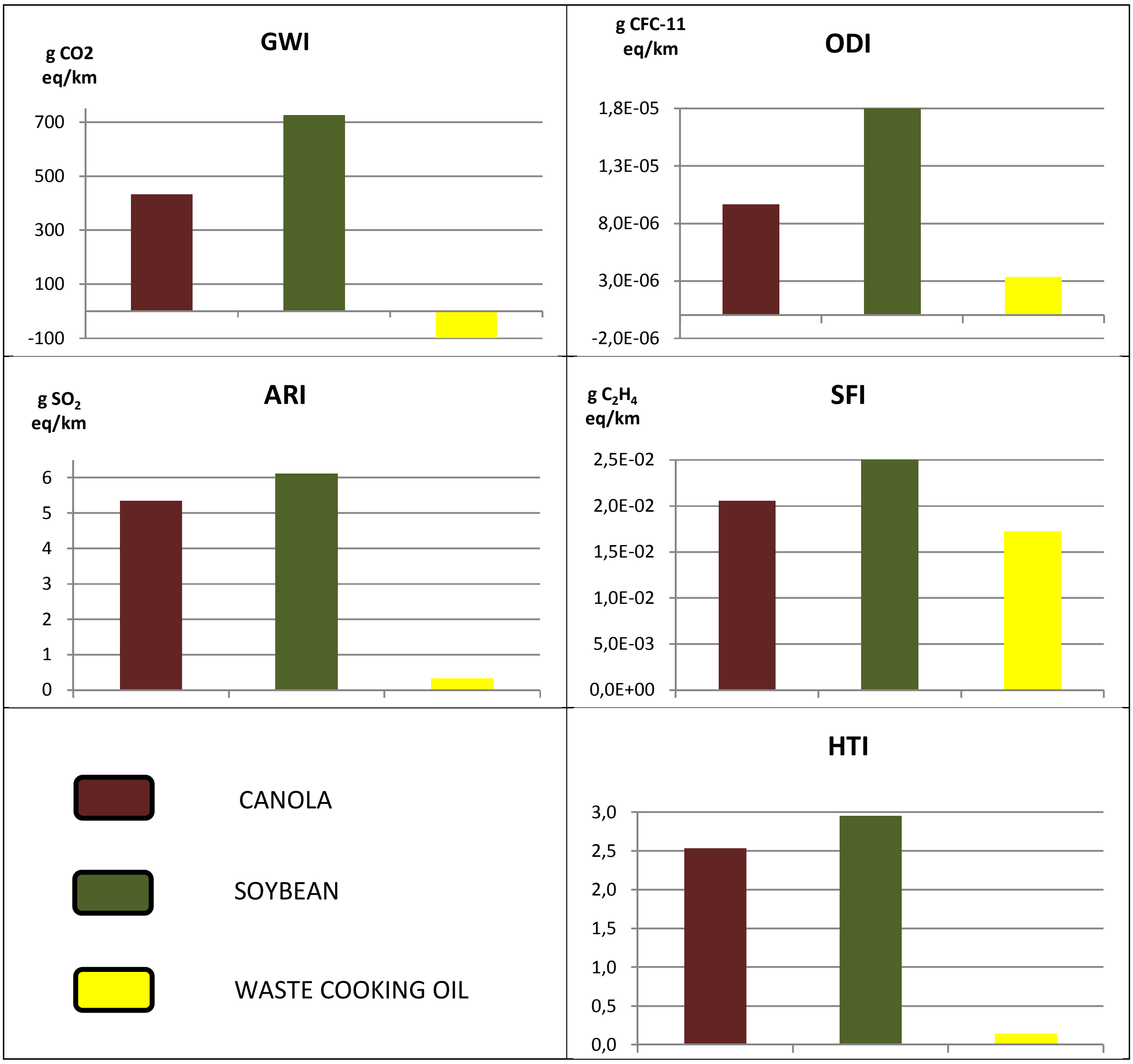

Figure 8: Graphical representation of the results - 1

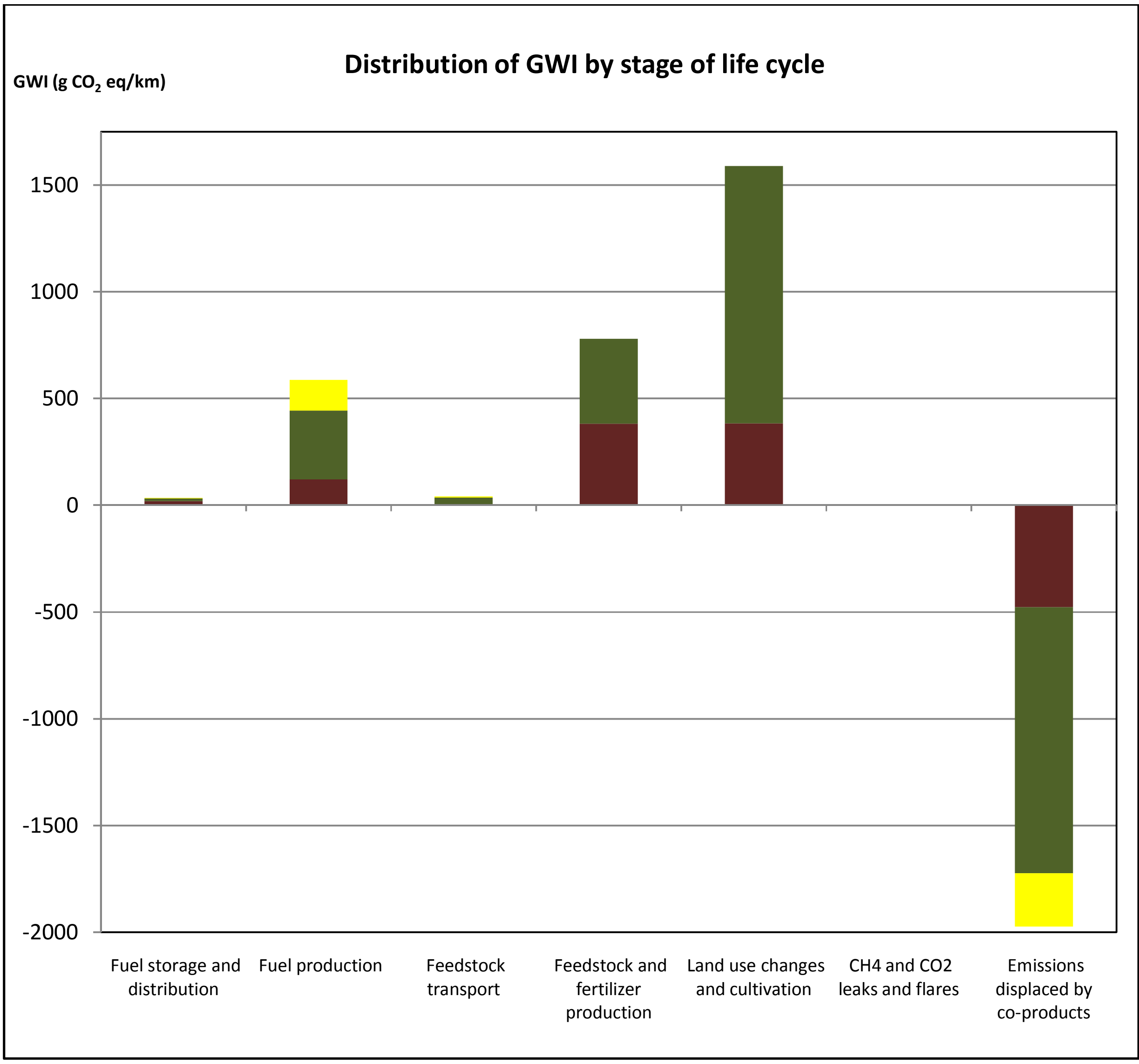

Figure 9: Graphical representation of the results - 2

4.3.2. Interpretation of the results

Two main conclusions can be drawn from these results.

- First of all, it clearly appears that, whether we consider one of the environmental impacts or the human toxicity impact, **biodiesel from waste cooking oil has the lowest impact, and biodiesel from soybean has the highest.** This is particularly true for the emission of CO_2-eq and can globally be explained by the fact waste cooking oil is considered as a waste of a previous utilization. Therefore, no emissions due to upstream operations (crop, fertilizers, etc) are considered for this biodiesel feedstock.
- The previous result is all the more obvious that **the GWI (in CO_2-eq) seems to be mainly due to three stages: “Land use changes and cultivation”, “Feedstock and fertilizer production”, and**

"Fuel production". As there is no emissions accounted for yellow grease biodiesel for the two first stages, it is logical that the summation on the life-cycle is lower than for canola and soybean biodiesel.

Besides, one could notice that:

- For the three options, the life cycle stage "Emissions displaced by co-products" plays a significant role in the decrease of the emissions. This is linked to the production of other compounds during oil processing such as commercial oils, meals, etc.
- Concerning the transportation step, it can be mentioned that trucks involve higher emissions than transportation by train; on the one hand, scenario #2 (soybean) has the longest transportation distances by truck and thus the highest emissions for this stage. On the other hand, scenario #1 (canola) emissions for this stage are quite close to the ones of scenario #3 (waste vegetable oil) although crops are coming from Alberta; one could see here that emissions from train transportation are noticeably lower than the ones for trucks.
- Contrary to what one might think, transportation steps have a quite negligible impact on the total impact of these biodiesel. "Feedstock transport" and "Fuel storage and distribution" are stages associated with the lowest emissions in term of Global Warming Impact as well as for the other impacts:
    - One can conclude that even if more "accurate" assumptions for transport distances had been made (cf. section 3.1. of this report), ranking of the three solutions would have not change and biodiesel from waste cooking oil would remain the lower emitter.
    - Furthermore, if waste vegetable oil was imported from Alberta and by truck for instance, the emissions for this stage would surely be higher than for the other scenarios but the overall ranking would remain identical.
- The only impact for which biodiesel from waste cooking oil seems to have a significant impact compared to the two other solutions is the Smog Formation Impact (even if this impact is still more important for soybean and canola options). This seems to be due to the production stage of the biodiesel from waste cooking oil which emits non negligible amounts of VOCs and methane.

These results and these conclusions make waste cooking oil of great interest concerning its utilization as biodiesel feedstock.

Conclusion

This term paper aimed at comparing biodiesel made from different feedstocks that can be used by UBC Fleet vehicles in order to lower the GHG emissions of UBC, and thus its impact on the environment. Three scenarios with different biodiesels have been analyzed: biodiesel from canola oil produced in Canada, biodiesel from soybean oil produced in United States and biodiesel from used vegetable oil collected on UBC campus restaurants.

A Life Cycle Analysis has been carried out by using the software GHGenius. The main objective of this study was to evaluate and compare the environmental impact of each type of biodiesel and finally determine whether the utilization of waste cooking oil from campus is the best solution in term of carbon footprint.

The results of this study show that biodiesel from waste cooking oil generates less emissions than Canola option, which itself generates less than soybean option. Therefore, it has been concluded that this biodiesel had the lowest environmental impacts (Global Warming, Ozone Depletion, Acid Rain Formation, and Smog Formation) as well as the lowest Human Toxicity impact.

However, many limitations to this study need to be pointed out. Indeed, some assumptions such as the biodiesel production process type have been integrated to the design of the software and could not be modified. Consequently, there might be some difference with the reality and the actual technology and this could change some life cycle results and thus real emissions emitted. Therefore, technical aspects, especially for biodiesel production, should be assessed in order to compare software assumptions and real production.

In addition, this term paper did not assess the cost for each biodiesel because too many assumptions should have been made. This aspect is also very important when doing a LCA because the solution that will be chosen must be economically feasible. Indeed, UBC is required to be “carbon-neutral” by 2010, thus economical point of view is also essential to consider. Therefore, both cost of the solution and savings due to the reduction in GHG emissions should be studied; this could be the purpose of another project and could maybe use the cost analysis that is also a part of GHGenius results.

But to do so, the scenario chosen have to be precisely defined; this is another limitation to this project. For instance, it has been assumed that a plant for biodiesel production from waste cooking oil would be in Vancouver; however the results could be different if another location is chosen.

All in all, and because the results of this project show important gaps between the three solutions in term of emissions, changes and inaccuracies should not modify the ranking of the three biodiesel options. It is thus highly recommended to consider waste cooking oil as a very interesting feedstock for biodiesel and further investigation should be made by considering the above limitations.

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Appendices

Appendix 1: Life-cycle stages considered in GHGenius

Feedstock production

Direct and indirect emissions from recovery and processing of the raw feedstock, fugitive emissions from storage, handling, upstream processing, fertilizer and pesticides manufacture, land use changes and cultivation, plants intake of carbon from air, etc.

↓

Feedstock transportation

Direct and indirect emissions from transport of feedstock, including pumping, compression leaks, fugitive emissions, transportation from field to refinery, etc.

↓

Fuel production

Direct and indirect emissions associated with the conversion of the feedstock into a fuel product, including process emissions, electricity generation, fugitive emissions, emissions from life cycle of chemicals used in the process, emissions associated with oil and gas production, emissions displaced by co-products of alternative fuels etc.

↓

Fuel transportation, storage, distribution and dispensing

Direct and indirect emissions associated with transportation of fuel, handling, storage, transfer from storage to vehicles, fugitive emissions, etc.

↓

Vehicle operation

Direct and indirect emissions associated with the use of the fuel in the vehicle, the manufacture and transport of the vehicle to the point of sale, the manufacture of the materials used in the vehicle, etc.

Appendix 2: Average Emissions data considered in GHGenius

Note: the following table give the emissions in term of gram of CO2 equivalent. However, in the software, the model is run with each separate pollutant.

Table: GHG emissions from Coal Fired Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	90,169	324.6
Upstream fuel emissions/unit fuel	2,833	10.2
Total/unit fuel	93,002	334.8
Total emissions/unit power generated	273,536	984.7
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	298,533	1,074.7

Table: GHG emissions from Fuel Oil Fired Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	71,148	256.1
Upstream fuel emissions/unit fuel	16,546	59.6
Total/unit fuel	87,693	315.7
Total emissions/unit power generated	258,133	929.3
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	281,810	1,014.5

Table: GHG emissions from Natural Gas Boiler Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	50,540	181.9
Upstream fuel emissions/unit fuel	8,585	30.9
Total/unit fuel	59,125	212.9
Total emissions/unit power generated	165,588	596.1
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	181,326	652.8

Table: GHG emissions from Natural Gas Turbine Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	50,796	182.9
Upstream fuel emissions/unit fuel	8,585	30.9
Total/unit fuel	59,381	213.8
Total emissions/unit power generated	116,542	419.6
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	128,074	461.1

Table: GHG emissions from Nuclear Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	1,875	6.8
Upstream fuel emissions/unit fuel	619	2.2
Total/unit fuel	2,494	9.0
Total emissions/unit power generated	2,494	9.0
g- CO_2-eq of N_2O/unit power delivered	940	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	4,243	15.3

Table: GHG emissions from Wind Power

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	0	0.0
Upstream fuel emissions/unit fuel	0	0.0
Total/unit fuel	0	0.0
Total emissions/unit power generated	0	0.0
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	1,535	5.5

Table: GHG emissions from Biomass Power

	g CO_2 eq/GJ		g CO_2 eq/kWh	
	Short Rotation Forestry	Wood Waste	Short Rotation Forestry	Wood Waste
Emissions from combustion/unit fuel	6	6	0.0	0.0
Upstream fuel emissions/unit fuel	-7,414	0	-26.7	0.0
Total/unit fuel	-7,408	6	-26.7	0.0
Total emissions/unit power generated	-17,297	15	-62.3	0.1
g- CO_2-eq of N_2O/unit power delivered	948	948	3.4	3.4
g-CO_2-eq of SF6/unit power generated	588	588	2.1	2.1
g-CO_2-eq/unit power delivered	-17,246	1,551	-62.1	5.6

Table: GHG emissions from Hydro Reservoir Systems

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	3,138	11.3
Upstream fuel emissions/unit fuel	0	0.0
Total/unit fuel	3,138	11.3
Total emissions/unit power generated	3,138	11.3
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	4,942	17.8

Table: GHG emissions from Hydro Run of River Systems

	g CO_2 eq/GJ	g CO_2 eq/kWh
Emissions from combustion/unit fuel	0	0.0
Upstream fuel emissions/unit fuel	0	0.0
Total/unit fuel	0	0.0
Total emissions/unit power generated	0	0.0
g- CO_2-eq of N_2O/unit power delivered	948	3.4
g-CO_2-eq of SF6/unit power generated	588	2.1
g-CO_2-eq/unit power delivered	1,535	5.5

Appendix 3: Results - Pollutants emissions for each biodiesel configuration and each life cycle stage.

CANOLA

Emissions (g/km)	CO_2	CH_4	N_2O	CFCs + HFCs	CO	NO_x	VOC - Ozone weighted	SO_x	PM
Fuel storage and distribution	12.3	0.018	0.003	1.44E-06	0.021	0.139	0.005	0.011	0.005
Fuel production	106.6	0.204	0.002	2.79E-07	0.077	0.221	0.335	0.122	0.518
Feedstock transport	3.1	0.003	0.000	3.07E-06	0.001	0.005	0.001	0.002	0.000
Feedstock and fertilizer production	315.5	0.492	0.045	2.11E-05	0.420	1.026	0.069	0.334	0.189
Land use changes and cultivation	-97.9	0.092	0.648	0.00E+00	0.000	6.958	0.000	0.000	0.000
CH_4 and CO_2 leaks and flares	0.0	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Emissions displaced by co-products	-253.1	-0.023	-0.537	-6.58E-06	-1.517	-1.355	-0.025	-0.015	0.000

SOYBEAN

Emissions (g/km)	CO_2	CH_4	N_2O	CFCs + HFCs	CO	NO_x	VOC - Ozone weighted	SO_x	PM
Fuel storage and distribution	8.4	0.016	0.002	1.62E-06	0.012	0.078	0.004	0.008	0.004
Fuel production	283.4	0.894	0.005	6.93E-07	0.154	0.435	0.357	0.427	0.567
Feedstock transport	28.4	0.043	0.001	3.68E-05	0.010	0.058	0.006	0.017	0.006
Feedstock and fertilizer production	314.8	0.743	0.045	3.08E-05	5.530	1.113	0.156	0.326	0.223
Land use changes and cultivation	-86.4	0.165	2.619	0.00E+00	0.000	11.908	0.000	0.000	0.000
CH_4 and CO_2 leaks and flares	0.0	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Emissions displaced by co-products	-252.3	0.214	-2.433	-3.36E-05	-6.640	-5.830	-0.101	-0.098	-0.006

COOKING OIL

Emissions (g/km)	CO_2	CH_4	N_2O	CFCs + HFCs	CO	NO_x	VOC - Ozone weighted	SO_x	PM
Fuel storage and distribution	2.7	0.004	0.000	1.08E-06	0.001	0.005	0.001	0.004	0.000
Fuel production	125.1	0.239	0.003	6.76E-07	0.094	0.260	0.337	0.134	0.016
Feedstock transport	5.0	0.007	0.000	4.89E-06	0.001	0.009	0.001	0.003	0.001
Feedstock and fertilizer production	0.0	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Land use changes and cultivation	0.0	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
CH_4 and CO_2 leaks and flares	0.0	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000
Emissions displaced by co-products	-249.8	0.000	0.000	0.00E+00	0.000	0.000	0.000	0.000	0.000

Appendix 4: Results - Sum up for each pollutant and each life cycle stage (in g/km)

	CO_2			CH_4			N_2O		
LIFE CYCLE STAGES	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL
Fuel storage and distribution	12	8	3	0.018	0.016	0.004	0.0031	0.0017	0.0001
Fuel production	107	283	125	0.204	0.894	0.239	0.0022	0.0052	0.0034
Feedstock transport	3	28	5	0.003	0.043	0.007	0.0001	0.0012	0.0002
Feedstock and fertilizer production	316	315	0	0.492	0.743	0.000	0.0446	0.0447	0.0000
Land use changes and cultivation	-98	-86	0	0.092	0.165	0.000	0.6484	2.6194	0.0000
CH_4 and CO_2 leaks and flares	0	0	0	0.000	0.000	0.000	0.0000	0.0000	0.0000
Emissions displaced by co-products	-253	-252	-250	-0.023	0.214	0.000	-0.5370	-2.4334	0.0000

	CO			NO_x			VOC - Ozone weighted		
LIFE CYCLE STAGES	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL
Fuel storage and distribution	0.0208	0.0123	0.0010	0.1387	0.0783	0.0049	0.0054	0.0036	0.0012
Fuel production	0.0775	0.1542	0.0935	0.2208	0.4350	0.2602	0.3347	0.3572	0.3367
Feedstock transport	0.0009	0.0105	0.0014	0.0054	0.0583	0.0086	0.0006	0.0058	0.0009
Feedstock and fertilizer production	0.4197	5.5305	0.0000	1.0259	1.1133	0.0000	0.0690	0.1564	0.0000
Land use changes and cultivation	0.0000	0.0000	0.0000	6.9577	11.9080	0.0000	0.0000	0.0000	0.0000
CH_4 and CO_2 leaks and flares	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Emissions displaced by co-products	-1.5174	-6.6397	0.0000	-1.3553	-5.8302	0.0000	-0.0253	-0.1010	0.0000

	SO_x			CFCs + HFCs			PM		
LIFE CYCLE STAGES	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL	CANOLA	SOYBEAN	WASTE COOKING OIL
Fuel storage and distribution	0.011	0.008	0.004	1.44E-06	1.62E-06	1.08E-06	0.0054	0.0038	0.0003
Fuel production	0.122	0.427	0.134	2.79E-07	6.93E-07	6.76E-07	0.5182	0.5672	0.0156
Feedstock transport	0.002	0.017	0.003	3.07E-06	3.68E-05	4.89E-06	0.0003	0.0056	0.0005
Feedstock and fertilizer production	0.334	0.326	0.000	2.11E-05	3.08E-05	0.00E+00	0.1890	0.2234	0.0000
Land use changes and cultivation	0.000	0.000	0.000	0.00E+00	0.00E+00	0.00E+00	0.0000	0.0000	0.0000
CH_4 and CO_2 leaks and flares	0.000	0.000	0.000	0.00E+00	0.00E+00	0.00E+00	0.0000	0.0000	0.0000
Emissions displaced by co-products	-0.015	-0.098	0.000	-6.58E-06	-3.36E-05	0.00E+00	0.0001	-0.0060	0.0000