Chapter 11

Environmental Assessment of a Forest Derived "Drop-in" Biofuel

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Additional information is available at the end of the chapter

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1. Introduction

The United States Department of Energy (DOE) has been championing efforts to ensure that the next generation of biofuels will be regarded as "drop-in" biofuels. According to the former DOE Undersecretary Kristina Johnson, "drop-in" biofuels can be defined as fuels produced from various biomass feedstocks which are compatible with the over $9 trillion energy refinery and gas station infrastructure currently in use in the United States [1]. The U.S. National Advanced Biofuel Consortium (NABC) considers it as infrastructure-compatible – they can either be used directly or blended with their petroleum-derived fuels. The European Commission (EC) defined it on the basis of quality specifications (standards) developed by the American Society for Testing and Materials (ASTM International) [2]. Thus, drop-in biofuels in any category (jet fuel, diesel, gasoline) should meet their respective ASTM D standards in order to be classified as such. Jet drop-in biofuels in this scenario are defined by the EC as fuels which meet the ASTM D 1655 and can be used either alone or blended to a certain percentage volume with a conventional fuel before its use (the final blend should have similar properties that meet the standards of ASTM).

Biofuel production involves extracting biomass materials from the environment, which are then transported to processing sites where the biomass is converted into biofuels. From these processing sites, the produced biofuel is then conveyed to end users through distribution points. However, it is critical to identify the effects of these activities and processes at each stage of the life cycle of biofuels with relevance to sustainable development – economic feasibility, environmental soundness and societal acceptability. A Life Cycle Assessment (LCA), which looks at describing the environmental profile of the whole supply chain of drop-in biofuels, has been looked at in this study.

Environmental LCA is a valuable life cycle assessment method used by scientists and researchers in order to assess the environmental aspects and potential impacts associated with a product, process or activity [3]. This assessment method, according to [3], involves four major steps - goal and scope definition, inventory analysis, impact assessment and the interpretation phase. LCA can be used to identify opportunities for improving the environmental performance of processes and activities, informing decision makers in industry, government and non-governmental organizations in order to aid them in strategic decision making and selection of relevant environmental performance indicators; and for marketing purposes (implementing an eco-labeling scheme, making an environmental claim, or producing an environmental product declaration (EPD)). There are two major types of LCA – the attributional LCA which uses average data for each unit process, and the consequential LCA which relies on marginal data for its analysis [4]. Additionally, attributional LCA analysis defines the status quo whilst the consequential LCA measures the impacts through changes in the physical flows.

LCA studies concerning drop-in biofuels are few considering that it is a relatively new form of advanced biofuel which aim to utilize existing infrastructures. However some studies conducted [5-7] emphasize the importance of this type of biofuel in reducing costs associated with replacing existing infrastructures with newly built ones which will be specifically designed for this biofuel type.

2. Problem statement

Meeting the energy needs of the world is necessary for continuous economic growth, enhancing social and even environmental benefits. It has become very clear that conventional biofuels won't be widely accepted if they cannot perform in the same way as conventional fuels. It is for these reasons that nations continue to search for new forms of primary sources of energy. Although this is critically important, an in-depth understanding of the effect of such activities on ecosystems is needed to help make better decisions which will drive the bio-energy revolution positively forward. This study forms part of such investigations.

3. Application area

The biofuel supply chain, according to [8 - 9], has been categorized into 5 phases – feedstock production, feedstock logistics, conversion technology, transportation and end-use of the fuel. For this research in particular, the life cycle stages considered are:

- Biomass production (forest raw materials)
- Biomass transportation
- Biomass conversion (chosen technological process)
- Fuel distribution

• Vehicle fuel use

The study examined the environmental impact of activities across the life cycle by considering the following impact categories across the phases/stages of the supply chain: climate change, eutrophication potential, acidification potential and most importantly, as a result of current discussions, land use change.

4. Research course

4.1. Goal and scope of study

This study of the environmental profile of "drop-in" biofuels production steadily examines the effects of the Thermal Deoxgenation (TDO) process to produce bio-crude from forest-based biomass, along its supply chain. This study aims to answer the following research questions:

- What are the environmental impacts at every stage of drop-in biofuel supply chain?
- What conclusions can be drawn from an LCA study of a relatively new form of advanced biofuel system?

This study is relevant to all stakeholders in the field of energy and environmental impact studies. The diagram below shows the supply chain that has been adapted from the biofuels supply chain described by the 2008 National Biofuel Action Plan [8].

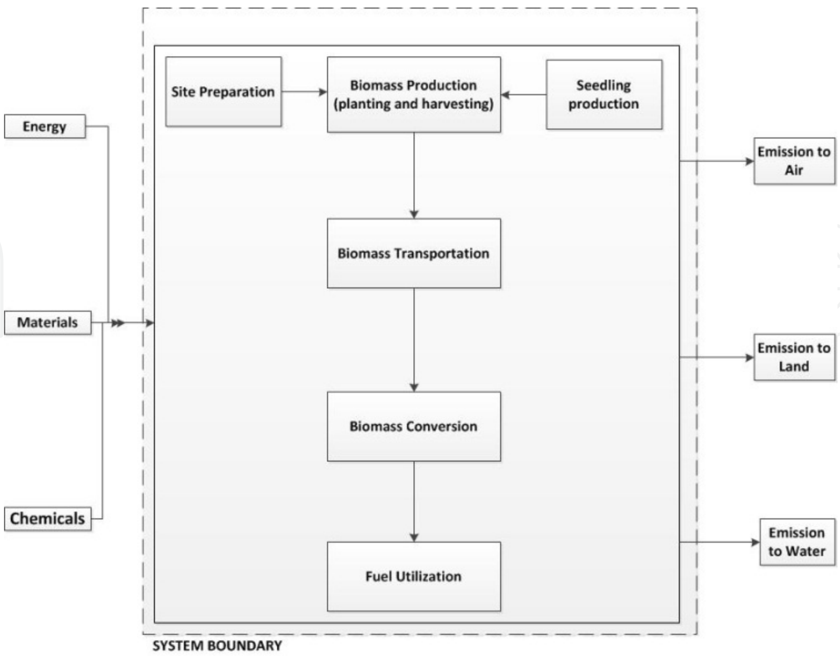

Figure 1. System boundary and process flow diagram for the research study

	Product Specific	Site specific	General	1	2	3	4	5	Comments and Major Literature consulted
Biomass Production									
seedling production	X	X					X		Values obtained from Neupane et al (2011)
site preparation	X	X					X		Values obtained from Neupane et al (2011)
stand preparation	X	X					X		Values obtained from Neupane et al (2011)
harvesting and processing	X	X					X		Values obtained from Neupane et al (2011)
			X		X				FAO (2010)
Biomass Transportation									
Fuel amount used for transportation			X		X				Simapro
Emissions			X		X				Simapro
Biomass Conversion TDO Process									
Electricity used	X				X	X			Data from UMaineEng/ Clayton Wheeler, Author
$Ca(OH)_2$ used	X			X	X				Data from UMaineEng/ Clayton Wheeler, Author
TDO Oil produced	X			X	X				Data from UMaineEng/ Clayton Wheeler, Author
Heat produced	X					X		X	Data from UMaineEng/ Clayton Wheeler, Author
H_2SO_4 Produced	X				X				Data from UMaineEng/ Clayton Wheeler, Author
Emissions produced (CO_2, NOX, CH_4)		X			X				US DOE
Fuel Distribution									
Bio- gasoline to be transported	X				X		X	X	Author
Fuel for distribution vehicles			X				X		Pradhan et al (2009), NREL
Emissions (CO_2, NOX, CH_4)	X		X		X				Date from EIA, EPA
Fuel Use -Biogasoline use									
Emissions (CO_2, OX, CH_4)			X		X				EPA

1. Measurement 2. Computations made by author 3. Data obtained from technology 4. Data obtained from similar technology 5. Approximation

Table 1. Data quality scoring system developed for the study

4.2. Functional unit

The functional unit used for all inputs and outputs used in the study is 1 liter of the TDO process drop-in bio-oil.

4.3. Method used

4.3.1. Data quality requirements

Data (e.g. fossil energy consumptions, carbon dioxide emissions) are analyzed carefully in order to map out the energy component and its associated emissions during the life cycle phases of the bio-oil. The raw material usage component which includes the use of land (the impact to be examined in that respect is land use change impacts) as well as Fertilizers, pesticides and other chemicals known for their use at any stage are accounted for by categorizing them into certain impact categories like acidification potential and eutrophication potential. The study follows procedures as stated in [10] and compiles data from existing databases available in Simapro, National Renewable Energy Laboratory (NREL), Environmental Protection Agency (EPA) as well as from literature in determining the effects with relevance to resource depletion, climate change and water use. A data quality scoring system is provided in Table 1 left.

4.3.2. Life cycle inventory analysis

In order to collect data in accordance with ISO 14040 guidelines, data representativeness, accuracy and consistency were considered. In most cases, specific data for the northeastern region and specifically for the state of Maine were used. For the processes elaborated on in subsequent parts of this study, the economic and environmental input and output flows have been calculated..

4.3.3. Allocation

It is understandable from the principles of LCA that inputs (resource consumptions), outputs and related environmental impacts can be allocated based on different basis (e.g. energy or mass basis). In this study, allocation was done with respect to mass basis of the amount of levulinic acid and formic acid (forming the bio-oil). This was necessary in calculating the amount of energy required in producing the TDO process oil only whilst considering other by-products like char, water and carbon dioxide.

4.3.4. Inputs and outputs

The table below shows all the inputs and outputs that were considered for the supply chain of drop-in biofuels.

Process (stage)	Inputs	Outputs
Biomass production	Nitrogen, phosphorus, potash for seedling production Water for seedling production Electricity for seedling production Fuel for site preparation, stand preparation and harvesting Lubricant for harvesting and processing	Harvesting of raw biomass Emissions
Biomass transportation	Fuel	Emissions –CO2, NOx, CH4, SO2, VOC, Volatile organic compounds
Biomass Conversion process (TDO)	Electricity Ca(OH)2	TDO Oil Heat H2SO4 Emissions-CO2 Steam
Fuel Distribution	Bio-gasoline from TDO oil Fuel for transporting bio-gasoline	Bio-gasoline Emissions-CO2, NOx, CH4
Fuel use	Bio-gasoline	Emissions- CO2, NOx, CH4

Table 2. Inputs and Outputs associated with each stage of the supply chain

5. Status and results

5.1. Biomass production

The biomass production process assumes 100% biomass supply from willow (tree diameter of 6 inches at 4 ½ feet just like Aspen [11] which is typically a hardwood (lignocellulosic biomass). The willow tree (S. alba) has a cell wall composition of 49% cellulose, 27% hemicelllose and 23% lignin [12, 13]. This stage of the supply chain was comprised of seedling production, site preparation, stand preparation, harvesting and processing. It was assumed that fertilizers were applied to aid the growth of the biomass. Data used for the early stage of biomass production in the state of Maine was obtained from Neupane et al.'s [14] work conducted on assessment of woodchips for bioethanol production.

The amount of harvested biomass was estimated to be 0.014102 tonnes based on the functional unit of 1 liter of bio-gasoline to be used by vehicles. Details of the 0.014102 tonnes include 18% of the described willow tree biomass on dry basis (a single tree). Nitrogen, phosphorus and potash applied were calculated to be 0.00818g, 0.0129g and 0.00818g, respectively. Water use amounted to 0.9 liters whilst electricity use, fuel use and lubricant use in the biomass production process were 0.0028 kWh, 0.936 liters and 0.04779 liters, respectively.

Total carbon dioxide equivalent emissions accounted for in this life cycle phase was 0.772kg.

5.2. Biomass transportation

The second stage of the biofuel supply chain involves the transportation of the biomass produced from the production site to the processing site (TDO processing point). The assumption of single unit trucks each weighing 60 tons [15] and making one trip per day was made for this phase of the life cycle. The choice of 72 kilometers in the project was based on previous work done by Neupane et al. [14]. From the calculations done, the resulting outputs of the unit process were emissions associated with the transportation CO2 (173g CO_2eq), NO_x (1.237g), CH_4 (0.0042g), dinitrogen monoxide (0.0062g), sulfur oxides (0.00327g) and VOC (0.0085g). The data used for the calculation of the emissions were derived from the Ecoinvent V2.1 database found in SIMAPRO.

5.3. Biomass conversion – TDO process

This process of biomass conversion to TDO which is unique to the University of Maine was used in the biofuel processing phase of the biofuel supply chain. This process produces a drop-in biofuel, which has been found to have boiling points similar to that of jet fuel, diesel and gasoline. Although further refining is needed in order to meet biofuel emission standards, all other technical properties make the new fuel attractive for use in existing fuel infrastructure without much further processing.

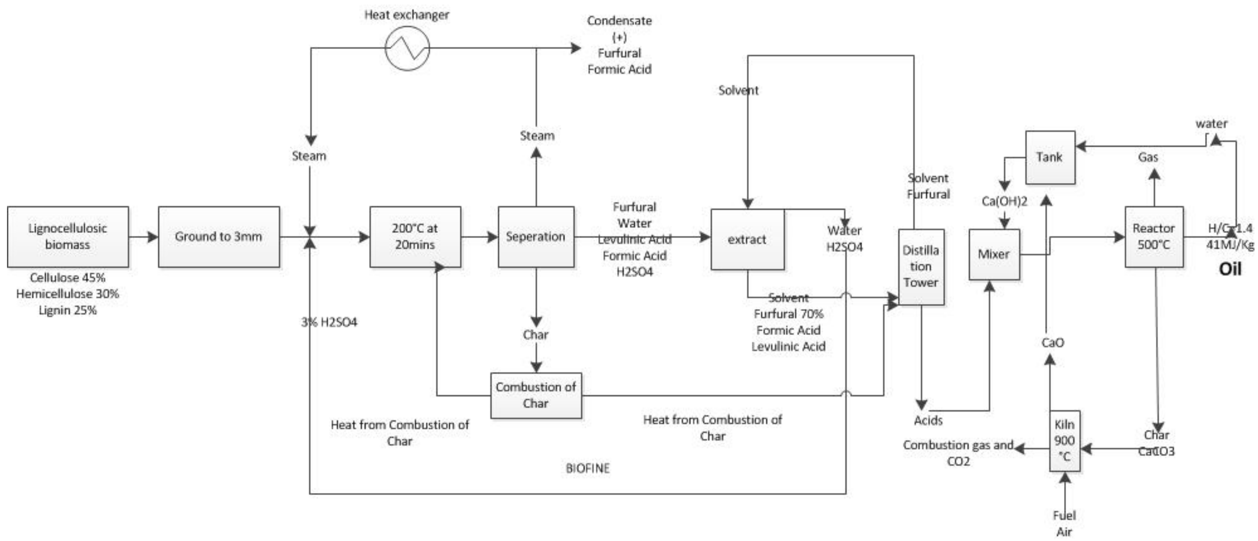

Figure 2. The TDO oil process diagram

This type of drop-in oil was produced through the thermal de-oxygenation process (TDO). This process starts with the conversion of cellulose to organic acids. The acids are combined with calcium hydroxide to form a calcium salt. The salt is heated to a higher temperature whilst being stirred. The resulting reaction from this stirring leads to the formation of a dark amber colored oil. The reaction also removes the oxygen from the oil. This key step (i.e. removal of oxygen) distinguishes the TDO process from other biofuel processes. The oxygen is removed as both CO_2 and water without the need for any outside hydrogen supply. Therefore most of the energy in the original cellulose is contained in the new oil. On mass basis, 13% of the initial lignocellulosic raw material is recovered as TDO bio-oil output. The oil has less than 1% percent oxygenates and has an energy value of 41MJ/Kg. The diagram below shows the TDO process[1] in detail.

From lab scale experiment, we found that to produce a liter of the final product of bio-oil (i.e. bio-gasoline), 0.09kWh of electricity was consumed over 24 hours. 0.077kWh of heat is also expended. Sulfuric acid which is produced in the system and recycled for usage is also needed as an input to treat 76% [13] of the raw material (Holocellulose). Outputs of this stage of the supply chain include the TDO oil (1 liter) – also the functional unit, Ca $(OH)_2$, NO_x(0.00246g), CH_4 (0.0056g) and steam (0.23[2]tonnes). This specific process did not produce carbon dioxide emission from the electricity usage because the primary source of energy for the electricity used is from the TDO biofuel. Most importantly, the biomass used for the TDO biofuel production is assumed to meet all sustainability criteria. As a result of this, there are no emission factors associated with it [16]. Secondly, since the carbon dioxide produced by the burning of the biofuel is offset by the biomass regeneration, it is technically justifiable to put the emisssion factor to zero.

5.4. Fuel distribution

This phase of the supply chain involves the transportation of the produced TDO oil to the distribution point where it will be used by vehicles or other usage facilities. It was assumed from average data gathered in the United States that 47% [17] of crude oil is converted into gasoline. Thus, from the 0.57 US gallon of TDO oil, 1 liter of bio-gasoline product is derived. With regard to the transportation fuel needed to convey the derived bio-gasoline product, it was assumed from literature that 0.08 gallon of fuel was needed to transport 1 gallon of biofuel (i.e. biodiesel) [18]. At the end, the total energy of the fuel used in transportation was estimated to be 0.183 kWh. Outputs of this stage included the transported bio-gasoline, and emissions – CO_2 (19.23g), NO_x (0.861g) and CH_4 (2.14g).

5.5. Fuel use

In the final stage of the supply chain, the major assumption was the choice of an EPA Tier 2 vehicle using an average of 9.6 liters of gasoline per 100km [19]. Through the use of 1 liter[3] of bio-gasoline, emissions produced included CO_2(2230g), NO_x (22.9g) and CH_4 (112.4g) [20]. Further analysis on the gathered data revealed the transportation stage as the most crucial stage due to the high energy usage and also the high amount of carbon dioxide associated with the energy usage. The following tables show some calculated linked flows normalized to the functional unit and the flows passing the system boundary.

1 TDO process description provided by Dr. Clayton Wheeler. University of Maine Biological and Chemical Engineering Department

2 Steam amount produced estimated by Dr Clayton Wheeler to be 200000lbs/hr

3 Calculated from Energy Information Administration, Documentation for Emissions of Greenhouse Gases in the U.S. 2005, DOE/EIA-0638 (2005), October 2007, Tables 6-1, 6-4, and 6-5. (Non-biogenic carbon content and gross heat of combustion for motor gasoline and diesel (distillate fuel))

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Total Energy Calculated	(kWh/FU)
Electricity	0.082418539
Fuel (gasoline)	2.76
Heat	0.069743855

Table 3. Total Energy Calculated

Total Water calculated	
Water (tonnes/FU)	0.120283142
Steam (tonnes/FU)	0.212063842

Table 4. Total Water Calculated

Charts were drawn to show graphically the contribution of each stage in the life cycle of the TDO drop-in biofuel. It is important to note in Figure 3, transportation stage contributes a major chunk of the carbon emissions associated with the supply chain.

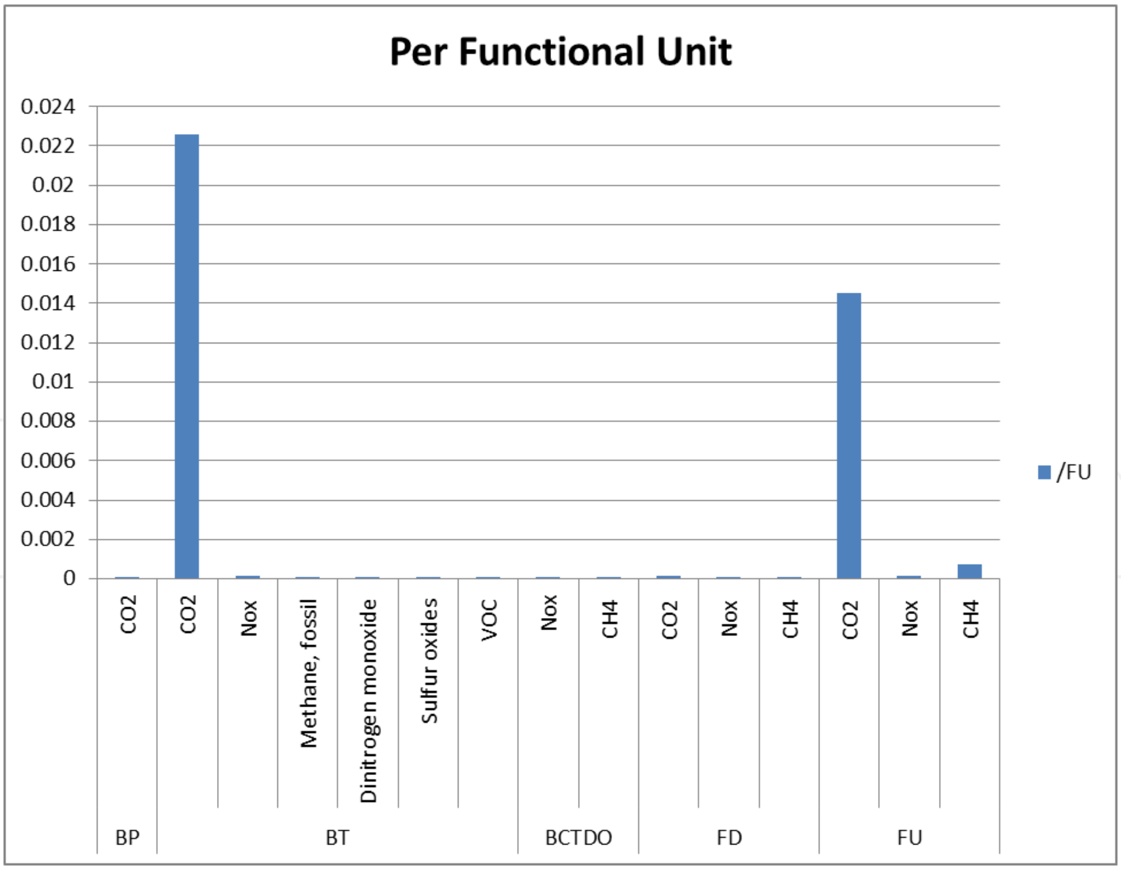

Figure 3. Chart showing life cycle emissions normalized per functional unit; BP=Biomass Production, BT= Biomass Transportation, BCTDO=Biomass conversion TDO Process, FD=Fuel Distribution, FU=Fuel Use

5.6. Life cycle impact assessment

According to the operational guidelines in the ISO standards of LCA, the impact assessment phase of LCA aims to make sense of the data obtained from the inventory analysis phase of the procedure. To interpret the environmental impacts and societal preferences, the following baseline impact categories were chosen in line with the CML method (refer to [21]): climate change, photo-oxidant formation, acidification, eutrophication potential.

Climate change: As stated by [22], this is expressed as

$$\sum_i GWP_{a,i} \times m_i$$

This indicator result is expressed in kilograms (Kg) of the substance of reference, CO_2. *GWP a,i* is the global warming potential for substance *i* over a period of years. *m* is the quantity of substance that *i* emitted over those years. *GWP* over a period of 100 years is used.

Photo-oxidant formation: According to [23], photo-oxidant formation is measured as

$$\sum_i POCP_i \times m_i$$

This indicator result is expressed in kg-ethylene equivalent. $POCP_i$ is the photochemical ozone creation potential for substance *i*. m_i on the other hand is the quantity of substance *i* emitted. In this case study, NO_2 was assumed to be 15% of the total NO_x emissions. This assumption was based on the paper by [24].

Acidification Potential: This potential impact category is expressed in kg-SO2 equivalent. The formula for calculating the potential value is

$$\sum_i AP_i \times m_i$$

AP_i is the acidification potential for substance *i* emitted to the air. m_i is the emission of substance *i* to the air [25].

Eutrophication Potential: The eutrophication potential is expressed as $\sum_i EP_i \times m_i$

This indicator unit is kg PO_4^{3-}. EP_i is the eutrophication potential for substance *i* emitted to air, water or soil whilst m_i is the emission of substance *i* to air, water or soil.

Impact category	Quantity	Unit	Normalization Factors	Normalized Values
Climate Change (GWP 100)	0.156335657	Kg CO2 equivalent	6.83E+03	2.29E-05
Photo-oxidant formation	0.000119795	Kg ethylene equivalent	8.04	1.49E-05
Acidification Potential	0.000320742	Kg SO2 -equivalent	5.29E+01	6.06E-06
Eutrophication Potential	4.3899E-05	kg PO43- equivalent	2.28E+01	1.93E-06

Table 5. Characterization of Chosen Impact Categories

The annual extent of the world's baseline impact categories (mid-1995) was used in normalization of the characterized results.

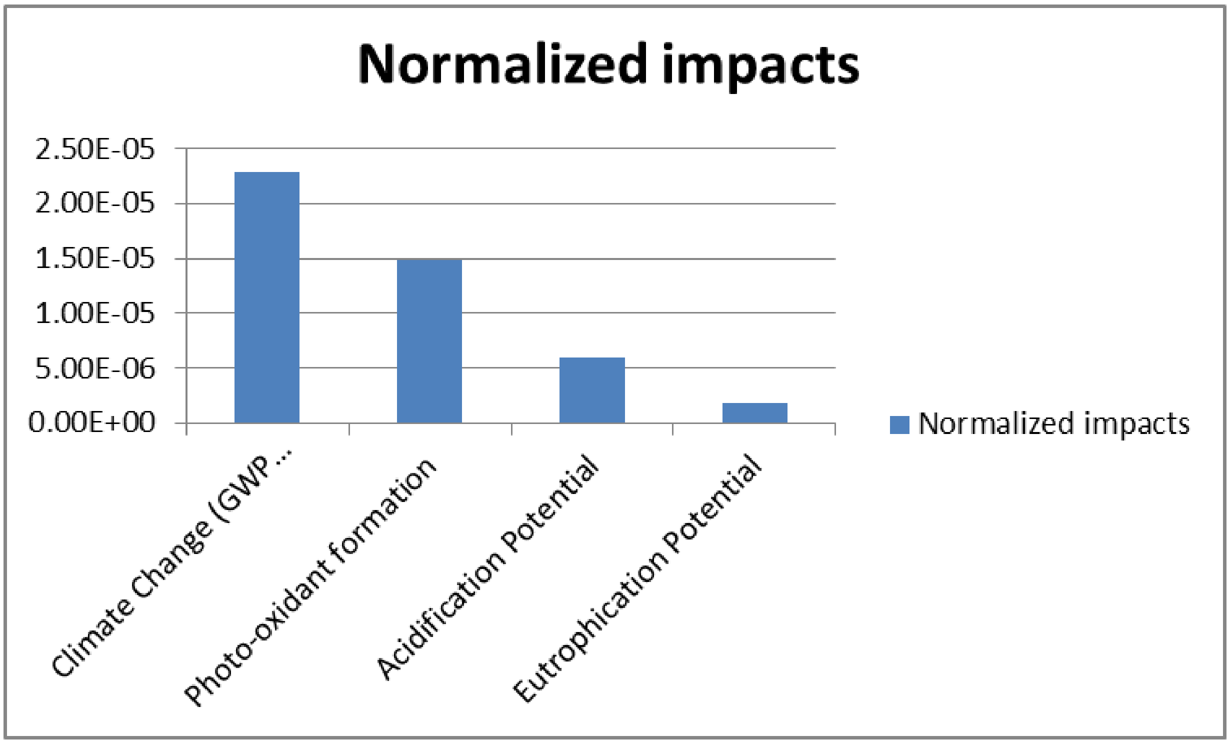

Figure 4. Normalized results showing the contribution of each impact to the environment relative to the functional unit of 1 liter of TDO oil

6. Discussion

6.1. Interpretation

Results obtained from the environmental profiling of the supply chain of the University of Maine TDO drop-in biofuel estimate the potential effects of the activities identified. Based on initial experimentation and inventory analysis, it was determined that the transportation phase of the bio-oil supply chain played a major role in the release of emissions to the environment. This was due to the high amount of fossil energy supplied externally that was assumed to be consumed in the transportation phase. The conversion step which was also observed to be energy intensive will have produced far bigger emission results if there was a reliance on electricity from the grid instead of using internally generated electricity with the TDO biofuel as its primary source.

Based on the inventory analysis conducted and after careful analysis, four major impact assessment categories were chosen: climate change (global warming potential), photo-oxidant formation, acidification potential and eutrophication potential. Many assumptions were also made in order to arrive at the results obtained. Such assumptions included the non-reuse of $Ca(OH)_2$ and sulfuric acid, which did not factor in the calculation of the impact assessment categories chosen.

The global warming potential (GWP) (100) impact assessment investigation revealed that in order to produce 1 liter of this new novel biofuel, 0.15kg of CO2 equivalent are emitted. The normalized results of this with respect to the worldwide normalization factor showed a value of 2.29E-6 for GWP. The highest contributor to this indicator of the amount of heat trapped in the atmosphere by the greenhouse gases emitted is the transportation sector (biomass transportation and fuel distribution), which as mentioned in earlier paragraphs involves the use of a very significant amount of fossil based energy in the form of electricity (supplied externally). It is important to note that transportation phase in the life cycle plays a significant role in the emission of large amounts of carbon dioxide which is also reflected in the calculation of the global warming potential.

With respect to photo-oxidant formation, 0.000119 kg of ethylene equivalent was released relative to the functional unit. Assumptions made from literature estimated the NO_2 composition of NO_X to be 15%. Based on this assumption, NO released along the supply chain accounted for close to 96% of the photo-oxidant formation potential.

Acidification potential (AP) and Eutrophication potentials (EP) are environmental effects that were important in understanding the environmental profile of the scaled-up TDO oil supply chain. The resultant AP and EP were estimated to be 0.00032 kg SO_2 equivalent and 4.38E-5 kg PO4 3- equivalent respectively. The normalized impacts in terms of global factors were calculated to be 6.06E-6 and 1.93E-05 respectively. The major contributing factor to the acidification potential was the NO component of the NO_x. This was also the case in the eutrophication potential. The phase which contributed the most to these impact assessment categories was the conversion phase. This was also associated with the external electricity supply for the conversion process.

7. Conclusion

This study initially evaluated the environmental life cycle impacts across the supply chain of a new drop-in biofuel, developed by the University of Maine (UMaine) College of Engineering, which is still at the bench scale. The study made use of primary data (available in UMaine Chemical Engineering Department) for the biomass conversion stage and utilized Maine's regional data as well as generic data developed in the United States. The study had a few limitations in terms of data quality and uncertainty. Important issues which are very relevant for LCA practices in the field of biofuel development and which have not been addressed in this paper were water and land use as well as the impacts on ecosystem goods and services. Land use change as a result of the activities involved in the growth and harvesting of willow is measurable in the sense that land use change (increase of land competition) can be estimated to be 35.9 m^2.yr (average age of willow in Northeastern America is 55 years to full maturity).

In the case of water use, it is clear from the inventory analysis that the biomass production phase requires a significant amount of water intake to enable the biomass to grow to maturity. A water intake of 0.120 tonnes shows the importance of finding a suitable source of water to use in the first phase of the life cycle and not relying on potable water for the growth of the biomass.

It is important to note that even though the global warming potential associated with carbon dioxide is very high, it should be understood that growing biomass actually helps reduce the atmospheric carbon dioxide in conjunction with photosynthesis. This actually leads to the conclusion that, compared to the conventional oil produced from fossil fuels, the UMaine TDO oil could be better. This is because, internal physiological processes of the biomass during the biomass production phase reduce the carbon dioxide emitted during the complete life cycle phase by using it to further the growth of the trees.

This study is an attributional LCA study, which can be further improved by a thorough life cycle sustainability assessment study [26] which takes into account the effects on the economic and social well-being of the stakeholders and the state of Maine in general. Such a study also advances that LCA is important in making decisions that will affect the long term sustainability of rural communities.

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