Life Cycle Assessment of Biodiesel Production from Microalgae: A Mass and Energy Balance Approach in Order to Compare Conventional with *in Situ* Transesterification

Gorkem Uctug, Divya Naginlal Modi, and Ferda Mavituna

***Abstract*—The aim of this work was to perform life cycle analyses (LCA) based on detailed process mass and energy balances for the production of biodiesel from microalgae in order to compare the conventional transesterification with in situ transesterification. GaBi software was used to perform the LCA. The material balances revealed that a slightly lower biodiesel yield was obtained for in situ transesterification process (5.06 kg/day) when compared to the conventional one (5.5 kg/day). GaBi results showed that the global warming potential (GWP) of the conventional transesterification process was higher than in situ transesterification by 140 kg CO_2 equivalent (per tonne of biodiesel produced). No substantial difference was noted however, for acidification (4.15 vs. 4.34 kg SO_2 equivalent), eutrophication (0.641 to 0.666 kg PO4-equivalent) and human toxicity potential (72.3 vs. 77 kg dichlorobenzene equivalent) between the two processes per kg of biodiesel produced. The results of the LCA analysis also show that electricity production was the major contributor for all the environmental impacts. When both the global warming potential and biodiesel yield were taken into account, it could be concluded that biodiesel production via in situ transesterification was a better option.**

***Index Terms*—Biodiesel, environmental impact, life cycle analysis, microalgae, transesterification.**

I. Introduction

The increasing demand for energy, the growing fears of climate change and other environmental issues and soaring prices of fossil fuels due to depleting fuel reserves are the main drivers for finding alternative sources of energy which are environmentally friendly [1], [2]. Extensive research has shown that biofuels are capable of replacing conventional fossil fuels in the transportation sector [3] and they have lower carbon emissions. Hence, biofuels are deemed capable of decreasing greenhouse gas emissions arising from the transportation industry [4]. Furthermore, biofuels contribute in reducing the dependency on conventional fuel sources in many countries [4] and they are equally considered to represent and compromise between meeting energy needs without causing further environmental damage [2]. Biodiesel is attracting interest due to several reasons, some of which are the following [5]-[7]:

i) it is biodegradable and has no toxicity characteristics,
ii) it has a lower contribution to air emissions,
iii) it can be produced from renewable precursors,
iv) it has negligible sulfur content, superior flash point and higher combustion efficiency
v) and it can be used in vehicles without modifying the engine due to the fact that biodiesel has the same physical and chemical characteristics as diesel.

Biodiesel can be produced via a variety of feedstocks, which are classified according to availability of use for other purposes. First generation feedstock (palm, rapeseed, soybean, coconut) have edible oils that are suitable for human consumption, second generation feedstock consists of oils that are inappropriate for human consumption (jatropha, karanja, jojoba, mahua, waste cooking oil, grease, animal fats), and finally third generation feedstock is defined as new products obtained from biological reactions/processes, such as microalgae [7]. Currently, the two most common feedstocks which are being used for producing biodiesel are rapeseed (in Europe) and soybean (in the United States). However, a debate is ongoing as to whether these two feedstocks should be primarily used as food or as a fuel source [8]. An alternative feedstock for biodiesel production can be algae. Amongst the numerous advantages associated with the latter, the most important one is that algae cannot be used as a food source so the problem of resource allocation between food and energy supply does not apply to the case of biodiesel production from algae [9]. However, it has been reported that it is imperative to have technological breakthroughs in the processing of algae so as to lower the environmental impacts below that of fossil fuel-based diesel [10], [11].

There have been several life cycle assessment (LCA) studies on algal biodiesel production but these have not considered mass and energy balances. The scope of this paper therefore, is to apply the mass and energy balance principle to perform a "gate to gate" LCA on biodiesel production from microalgae. The objectives of our study are as follows:

vi) To build two hypothetical models of microalgal biodiesel production. The former model is based upon the information available from literature on biodiesel production from Chlorella using raceway ponds of seawater in India with the conventional transesterification. The model consists of using an alternative route that uses in situ transesterification, which is believed to be more efficient. These models are considered herein so as to determine whether in situ transesterification has a lower environmental impact.
vii) To perform a mass and energy balance on the models for the process. The aim of performing these balances is to

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build the inventory analysis which will then be used to perform the LCA.

viii) To analyse several examples of environmental impact based on the data obtained from the mass and energy balances and comparison among such instances so as to determine the best route of biodiesel production from microalgae.

II. Methodology

A. Biodiesel Production from Microalgae

There are several major and minor processes associated with the production of biodiesel from microalgae. These processes are summarised in Table I.

TABLE I: Major and Minor Processes in Biodiesel Production from Microalgae

Process Classification	Unit Process
Major	Cultivation
	Harvesting
	Oil extraction
	Transesterification and *in situ* transesterification
	Anaerobic digestion
Minor	Transportation of biomass within the industry through a belt conveyor
	Separation of algal residue from oil
	Hexane and methanol recovery from oil
	Neutralisation of catalyst
	Separation of glycerol from biodiesel
	Purification of biodiesel

Since the main novelty of this paper is to compare two different transesterification methods, we believe that a special focus should be given to transesterification. Transesterification can be defined as the process whereby triacylglycerols (TAGs) are converted into fatty acid methyl esters (FAME) in the presence of an alcohol and a catalyst [12].

In situ transesterification, on the other hand, consists of performing oil extraction and conversion of oil into biodiesel through a single step. The advantages of *in situ* transesterification over conventional transesterification is the reduction in the manufacturing cost due to the elimination of certain unit processes such as oil extraction using hexane, and simplicity of system design and operation [13], [14]. However, *in situ* transesterification has certain disadvantages as well such as the decrease in the biodiesel yield and the increased consumption of chemicals due to the requirement of a higher ratio alcohol-oil ratio [15].

B. Mass and Energy Balance Approach

Since there are no known existing commercial plants which produce biodiesel from microalgae [16], the models used in this research were built based on the information available from the literature, especially for the cultivation of the microalgae as shown in Table II. In this paper, the inputs and outputs were determined using a chemical engineering approach, that is, mass and energy balances rather than just collecting data about the process. Although biodiesel production from microalgae is still in its infancy on the commercial scale, much research has been carried out about the unit operations involved in the process. In this study, two scenarios of mass and energy balances have been carried out. The first scenario (also referred to as the baseline scenario) consists of using the conventional method of producing biodiesel whereas the second scenario (*in situ* transesterification) involves using a more advanced technology so as to minimise cost and process units. Detailed information about the mass and energy balances can be found elsewhere [17].

TABLE II: Data for the Mass and Energy Balance Calculations

Parameters	Values	References
Maximum specific growth rate	0.041 h^{-1}	[18]
Initial dissolved CO_2 concentration	0.013 $mol \cdot m^{-3}$	
Michaelis- Menten constant of CO_2	0.00021 $mol \cdot m^{-3}$	
Surface area of raceway pond	10,000 m^2	[19, 20]
Depth of raceway pond	20 cm	[20]
Biomass concentration in pond	0.1 $g \cdot L^{-1}$	[18]
CO_2 utilization efficiency	90%	[21, 22]
Amount of CO_2 consumed by microalgae daily	540 kg	[22]
CO_2 loss	25%	[11, 23]
Ratio of C:N :P	100:16:1	[23]
Amount of water lost due to evaporation per square metre	0.0062 m^3	[24]
CO_2 utilization efficiency	90%	[21, 22]
Organic carbon content of microalgae	50%	[25]

C. Life Cycle Assessment (LCA) Methodology

The scope of this study consists of analysing 1 kg of algal biodiesel produced at factory gate through the conventional esterification method and *in situ* transesterification. System expansion is applied in this study for both production routes, as follows; algal residue is anaerobically digested to produce biogas and is in turn combusted to generate electricity which is used in the cultivation process. Similarly, glycerol is combusted in a furnace to generate heat which is used within the biodiesel production process. The environmental impacts were calculated by using GaBi software with CML2001 methodology. The main reason behind this choice is that the same methodology has been adopted by several authors [11], [16] who previously carried out LCA research on biodiesel. The biodiesel production is assumed to take place in India using raceway ponds with seawater.

The system boundary for the production of biodiesel through the conventional method and *in situ* transesterification are represented by Fig. 1 and Fig. 2, respectively. The following unit processes have not been considered in this project:

- construction of the biodiesel plant;
- transportation of raw materials and of process equipment;
- manufacturing process of raw materials (except electricity) and process equipment;
- transportation of biodiesel to the filling station, and;
- combustion of the biodiesel produced.

Detailed information about the LCA inventory can be found elsewhere [17].

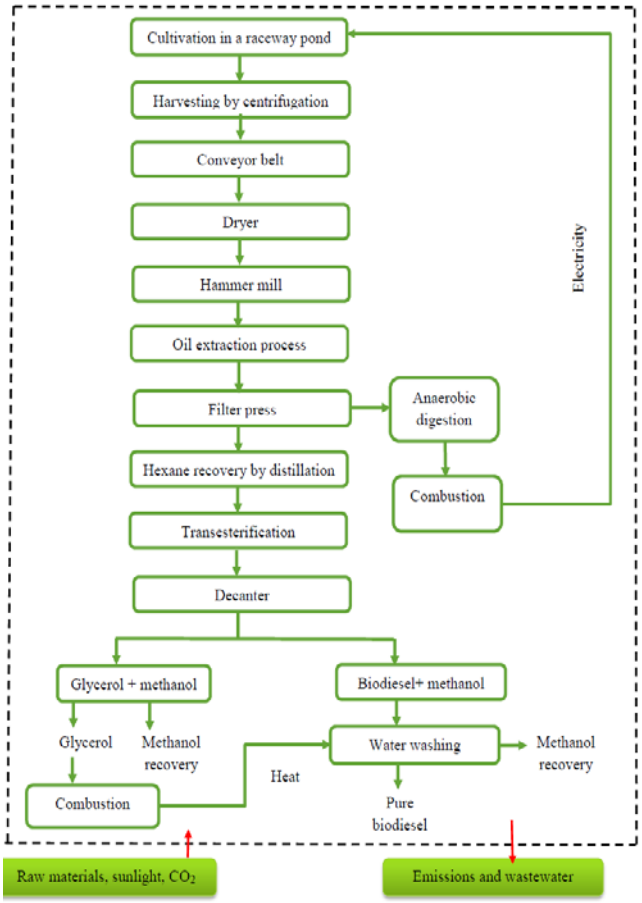

Fig. 1. System boundary for conventional algal biodiesel production.

In the two models salt water algae such as the genus *Chlorella* is used. The cultivation is based on open raceway ponds with the injection of carbon dioxide (flue gas). Paddlewheels are used in order to provide mixing of the dissolved carbon dioxide and other nutrients, sodium nitrate and diammonium phosphate solution. The operating period for the raceway pond is assumed to be 10 hours. During the night, it is assumed that the algae will not grow.

Algal oil was assumed to consist only of linoleic acid (C18:2) since it has been observed to be the most abundant fatty acid present in microalgae [26]. Linoleic acid was therefore used in the estimation of the stoichiometric carbon requirement by microalgae for the formation of the fatty acids.

III. Results and Discussion

Fig. 3 below shows the comparative impact results for conventional and in situ transesterification, as well as the yield scores for each technology.

A. Global Warming Potential

Based on Fig. 3, it is estimated that irrespective of the method of biodiesel production considered, an average of 2.26 kg CO_2 eq. per kilogram of biodiesel produced is emitted. The results from the GaBi software revealed that in both scenarios, electricity production is the major process which contributes most to the release of GHG gases. In this work, electricity production has been modelled using coal as its precursor material. Using coal as a raw material for electricity production leads to the release of massive amounts of CO_2, CH_4 and NO_X. The CO_2 emission, which is reported in the GaBi software to contribute to global warming, is, in fact, the excess CO_2 not consumed by the microalgae and, consequently, released into the atmosphere. In order to further increase the amount of CO_2 consumed by microalgae, new approaches to facilitate CO_2 consumption by the algae must be developed.

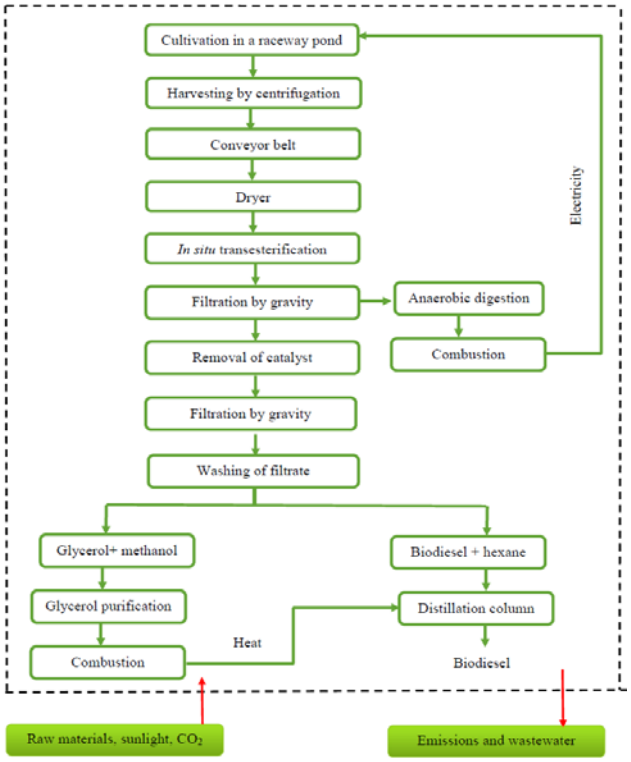

Fig. 2. System boundary for in-situ transesterification in algal biodiesel production.

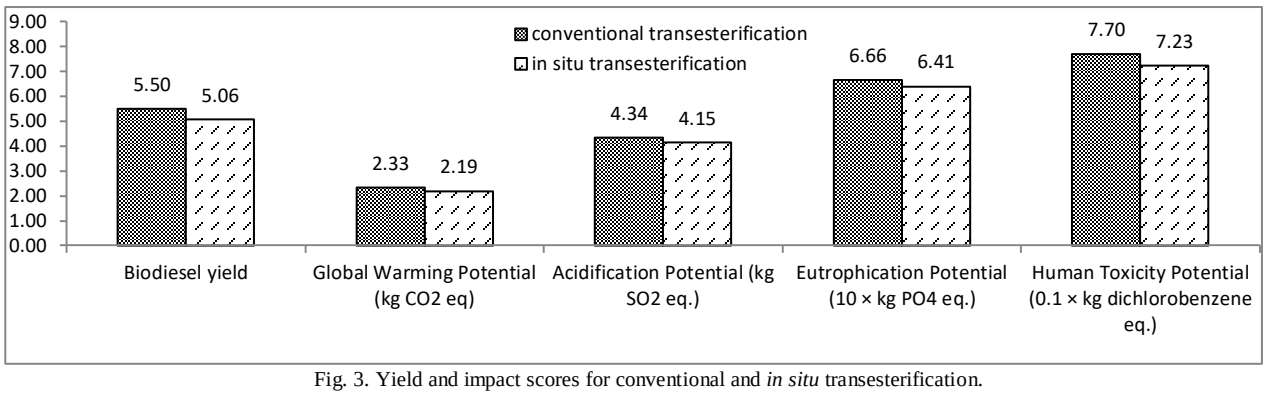

Fig. 3. Yield and impact scores for conventional and *in situ* transesterification.

B. Acidification Potential

The range of acidification potential of microalgal biodiesel production was found to vary between 4.15 to 4.34 kg SO_2-eq. per kilogram of biodiesel produced. The GaBi analysis proved that electricity and cultivation of microalgae are the major contributors to the effect of acidification. The emissions produced during electricity generation which contribute to the effect of acidification include NO_X, hydrogen chloride (HCl) and NH_3. Fertilisers are believed to be the main cause for NH_3 emissions [11]. It can be observed that there is a very small difference in the acidification potential between *in situ* transesterification and conventional transesterification. Hence, it can be argued that this difference is relatively insignificant on an industrial scale, for example for the production of 1000 kg of biodiesel. The marginal difference is due to the fact that the electricity consumption in *in situ* transesterification is less than in conventional transesterification.

C. Eutrophication Potential

Regardless of the method of biodiesel production considered, the eutrophication potential varies between 0.666 to 0.641 kg PO_4^{3-} eq. per kilogram of biodiesel produced. The major contributors of eutrophication are electricity production and cultivation of microalgae. GaBi revealed that NH_3 is the major pollutant leading to the effect of eutrophication. Similar findings have been observed in earlier studies [27].

D. Human Toxicity Potential

From Fig. 3, it can be speculated that there is a minimal difference of about 6.1% between the two scenarios. If the above scenarios are modelled for large scale biodiesel production, the savings in terms of human toxicity potential in in situ transesterification are not substantial. Human toxicity is caused mostly through emissions into air, which is equal to 68.2 kg DCB eq. and 64.1 kg DCB eq. for conventional and in situ transesterification, respectively (both are expressed in units of kilogram of biodiesel produced). A stage contribution analysis of the GaBi results showed that electricity production is the sole key contributor to human toxicity. This result conforms to earlier findings [27]. The pollutants released from the production of electricity consist mostly of heavy metals (41.3%) such as arsenic (+V) and selenium, inorganic emissions to air (23.2%) and organic emissions to air (23.5%) for in situ transesterification. This result is in agreement with findings in earlier studies [27] that emissions of heavy metals are responsible for human toxicity.

E. Comparison to Other Studies

Although there is a considerable number of studies concerning the LCA of microalgal biodiesel in the literature, direct comparison of our results to the results published in those studies proved to be impossible in most cases due to either differences in system boundaries or in functional units. For instance, many studies define the functional unit as the unit amount of energy produced in a vehicle. Furthermore, the type of LCA methodology used (endpoint vs. midpoint) also limits the scope of comparisons of the respective results. Finally, even if the system boundaries, functional units, and methodologies are similar, the impacts calculated in one study may have been overlooked in another. It was therefore only possible to compare the global warming potential results with four other studies. Results of these comparisons are presented in Fig. 4.

Fig. 4. Comparison of Global Warming Potential (GWP) values against other studies.

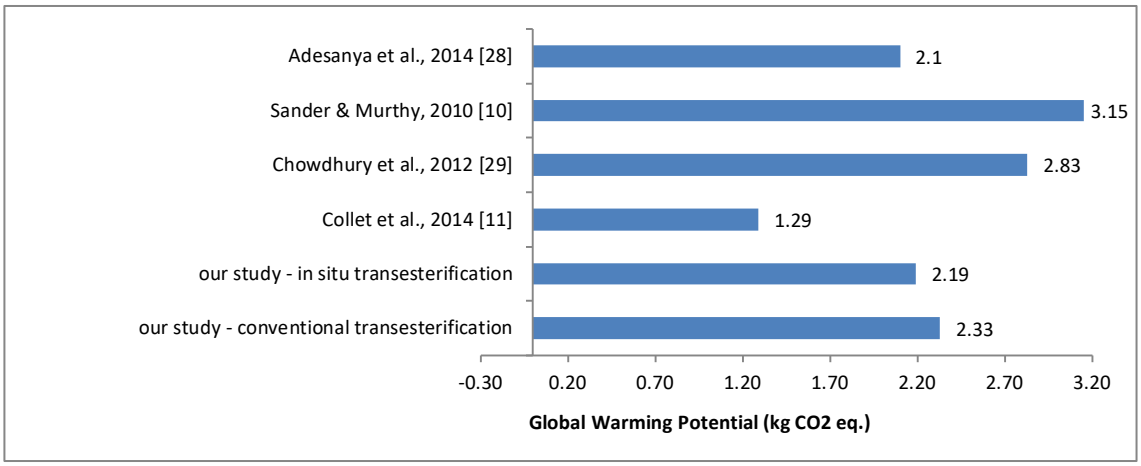

Fig. 4 shows that our results are close to, albeit not the same as, the findings reported in earlier studies. The main differences arise from the environmental qualities of the sources used for electricity generation. For instance, Collet and colleagues [11] used the European electricity mix data, which has much lower GWP impact than the Indian electricity mix, and we believe this to be the main reason behind the considerable difference between their results and ours.

Last but not least, we would like to explain the absence of a sensitivity analysis in this study. Since the present approach is based on a detailed mass and energy balance, we believe that all the inventory data are of high quality and therefore we deem any sort of sensitivity analysis unnecessary.

IV. Conclusion

In this study, two hypothetical models; conventional and *in situ* transesterification, were developed as potential methods of producing biodiesel from microalgae. The two systems considered for biodiesel production consist of unit operations that were modelled in the best possible realistic way. It can be

stated that *in situ* transesterification have never been considered in previous LCA studies on microalgal biodiesel production. A combination of the technologies applied in the downstream processing of first and second generation biodiesel feedstocks were applied to the microalgal biodiesel production systems. Mass and energy balances were performed and used to build the inventory for the LCA on biodiesel production. The material and energy balances carried out indicated that the biodiesel production process has a relatively low efficiency. However, algae can have up to 100 times more oil content when compared to first and second generation feedstocks (energy crops). Also, *in situ* transesterification has a slightly lower biodiesel yield than the conventional transesterification method. An analysis on the possible environmental impacts that may arise from the biodiesel production process has been carried out. The LCA analysis revealed the following:

- *In situ* transesterification has been proved to perform better across all the impact categories considered in the present work. This is due to the fact that the conventional transesterification process has slightly higher energy consumption.
- The global warming potential of *in situ* transesterification is lower than that of the conventional transesterification. The former has a GWP of 2190 kg CO_2-eq. whereas the latter has a GWP of 2330 kg CO_2-eq.
- The difference observed amongst the environmental impacts (besides global warming potential) is marginal and consequently, it may not make a significant difference on the consequences of acidification, eutrophication and human toxicity.
- In both scenarios, the effect of acidification has been found to be caused mainly by electricity production and cultivation of microalgae. The use of fertilisers in the cultivation medium has been observed to be responsible for the acidification effect due to the release of NH_3.
- Results given by GaBi revealed that eutrophication is mostly a result of electricity generation and the cultivation process of microalgae. NO_X and NH_3 are the major pollutants released from each of these processes, respectively.

Algal photosynthetic and primary carbon metabolism play a very important role not only in the process economics but also in the LCA-indicated sustainability issues for future considerations of algal hydrocarbon and/or biodiesel production. Strain improvement either through natural mutant identification or genetic manipulations, with the proper containment precautions, should be the alternatives to consider as far as future work is concerned.

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