Biodiesel From Microalgae – A Sustainability Analysis Using Life Cycle Assessment

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ABSTRACT

Dwindling oil prices and limited reserves of fossil fuels have spurred widespread interest in finding renewable sources of energy. Biodiesel is one such alternative fuel which has provided an alternative to petroleum diesel. Biodiesel can be produced form oil derived from variety of biomass such as soybean, jatropha, rapeseed, sunflower etc. However, large areas of cultivations land is required to grow these plants and hence has drawn a lot of flak as the same land could otherwise be used for food crop cultivation to feed the ever growing population around the world.

This study evaluates the environmental sustainability of biodiesel production process using microalgae as biomass. High oil yields with respect to the area used have attracted widespread interest in research on use of microalgae as a potential feedstock for producing biofuels. Algal biomass is obtained by cultivation of the selective species of algae, harvesting followed by extraction of oil, which is converted to biodiesel by the process of transesterification. In this study, Life Cycle Assessment (LCA) is carried out on the biodiesel production process from microalgae.

A virtual system has been devised for the study with material and energy input streams derived from available literature on the process and the system has been evaluated for various impact parameters. A comparison at the cultivation stage between open pond culture and photobioreactors revealed that open pond has lesser environmental impact while mechanical extraction was found out to have lesser value for Global Warming Potential (GWP) than chemical extraction in the extraction stage. Harvesting stage was determined as the most energy intensive stage with 40% of the total energy consumed in the process going into this stage.

Keywords: Microalgae; Biodiesel; Life Cycle Assessment; Global Warming Potential.

Biodiesel from Microalgae – Third Generation Biofuel - Introduction

With the ever growing world population and technological advances in all works of life, world energy demand is expected to rise by 44% while CO_2 emissions will see an increase of 39% by the year 2035.[1] With growing concerns associated with fossil fuels a large amount of this energy need will have to be satisfied using renewable sources. In India the crude oil imports for year 2009-2010 increased by 60% from the year 2005-2006[2] and are expected to only rise in coming years to sustain the growing economy.

Transportation accounts for almost 30% of the world's energy consumption most of which is in the form of liquid fuels.[1] Biofuels (fuel obtained from biomass) could play a major role in substituting the use of crude derived fuel in transportation as there are no major changes required in the design of engines compared to other alternative sources which are in different physical states. The biofuels used in transportation sector are bio-ethanol and biodiesel. Biodiesel can be used in its pure form however is usually blended with petro-diesel. Biodiesel has been gaining popularity not just because it is obtained from renewable sources but also because it has many advantages over petro-diesel. It is as biodegradable as sugar, ten times less toxic than table salt and has a higher flash point (100-170°C) compared to petroleum diesel fuel (60-80°C).[3]

The growing demand for biodiesel is evident from the increase in world biodiesel production which doubled in 2011 from its value in 2007.[1] Biodiesel is obtained by transesterification of oil crops (rapeseed, sunflower, soybean, palm oil etc.). The oil from these crops contains triglycerides which are reacted with methanol to give fatty acid methyl esters (FAME) which is biodiesel.[4] Biofuels obtained from the above mentioned sources are called as first generation biofuels while the second generation biofuels are produced from crops such as *Jatropha*, cassava or *Miscanthus.*[5] However in both first and second generation biofuels vast areas of arable land is required to cultivate these plants, the land which otherwise could have been used to cultivate food crops to feed the rising population of the world. This problem could be solved using the third generation biofuels which are obtained from microalgae, seaweeds and microbes.[6]

Algae grow in aqueous medium in the presence of sunlight and require large amounts of carbon dioxide. For production of 60 billion gal/year of biodiesel at a productivity rate of algae at 50 $g/m^2.d^{-1}$ with 50% triglycerides, the CO_2 required for necessary algae cultivation would be 0.9 billion ton/year which is 36% of the total US power plant emissions.[7] Hence algae cultivation can effectively be used as a CO_2 sequestration technique. The other nutrients required for cultivation such as nitrogen and phosphorus can be obtained from organic waste from agri-food industry.[8] However, the major advantage of microalgae over other oil crops used for production of biodiesel is the oil yield per acre of land used. Soybean cultivation gives 48 gallons/acre of oil yield, for *Jatropha* it is 202 gallons/acre, yield of palm oil is slightly higher at 635 gallons/acre. However, algae with a growth of 10 g/m^2/day at 15% triglyceride content can give 1200 gallons of oil per acre and the yield can go up to 10,000 gallons/acre for algae with 50% triglyceride content at a growth rate of 50 g/m^2/day.[7]

Although microalgae have tremendous potential in terms of reducing greenhouse gas (GHG) emissions and dependency on fossil fuels there are many hurdles which have hindered the commercialization and extensive use of microalgae for production of biodiesel. In addition to various technological and economic issues such as pre-treatment, enzyme production, commercial scale deployment, cost of the biodiesel produced etc.,[6] it is very important to look at the environmental impact of setting up a large scale biodiesel production facility using microalgae.

In view of the above discussion it is important to study in detail the environmental impacts of implementing such technologies and their sustainability to avoid 'problem shifting' or "The displacement or transfer of problems between different environmental pressures, product groups, countries or over time." For example, extensive use of fertilizers for growing crops for biofuels could lead to increased nitrous oxide (N_20) emissions which have higher Global Warming Potential (GWP) than CO_2. Life Cycle Assessment (LCA) which is defined by International Organization for Standards (ISO, 1997) as a "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." is an effective tool which can be used to analyze the sustainability of any proposed technology. In this work, LCA is used to study the environmental impact of the various stages involved in the life cycle of biodiesel produced from microalgae and also to compare alternatives in the cultivation and the extraction stages in the production chain.

Life cycle of biodiesel production from microalgae.

There are around 50,000 different species of microalgae all over the world [Richmond, 2004]. Lipid content and the composition of free fatty acids play a major role in the selection of the species for biodiesel production.[9] The lipid content of the *chlorella* species can vary from 10-48% of dry weight biomass in *chlorella sp.* and can go up to 63 % in *chlorella emersonni* and have been described as the most suitable species for production of biodiesel by Mata et.al[9] in a review paper.

In the first stage of the process, the desired species is cultivated by photoautotrophic production in open ponds or closed photobioreactors (PBR). The open ponds are around 0.25-0.30 m deep with a motor operated paddle wheel for constant circulation and mixing and the CO_2 requirement can be fulfilled by surface air or from waste streams from industries such as flue gas.[10] Photobioreactors could be tubular, flat plate or column, each having their own advantages and limitations.[11] Single species culture and growth of more sensitive strains is possible in PBRs resulting higher cell mass productivities than that in open pond culture.[12] A comparison of environmental impacts of these two methods of algae cultivation has been done in this study.

The next stage, harvesting can be divided into two steps, the first step being separation of the biomass from the bulk suspension to reduce the concentration to 2-7% total solid matter. Flocculation, flotation or gravity sedimentation can be used for this step. This is followed by concentration of the slurry by dewatering using techniques such as centrifugation, filtration and ultrasonic.[11] In a LCA study done by Lardon et.al[13] normal culture and low nitrogen culture was evaluated in the open pond cultivation system while flocculation was used as a technique for harvesting using synthetic flocculants and lime, followed by rotary press filtration. In this study PBR is also studied along with open pond culture for cultivation and natural settling followed by centrifugation is considered at the harvesting stage.

Mechanical extraction of algal oil can be done using expeller press or by ultrasonic extraction while extraction using hexane, Soxhlet extraction and supercritical fluid extraction are some of the chemical extraction methods that can be used.[14]

Transesterification is the most common process used to convert the triglycerides in the extracted oil into biodiesel or fatty acid methyl esters by reacting with methanol.[16] Alcohol is used in 100% excess to ensure maximum conversion of triglycerides into FAME. Yield of methyl esters may exceed 98% on weight basis.[17] Sodium hydroxide or potassium hydroxide is usually used as a catalyst at a concentration of about 1% by weight of oil and requires a lot of water and energy for separation of biodiesel and glycerol after the reaction.[4]

A virtual system is designed in this study for production of biodiesel from microalgae using information available in the literature and simulating the process on a process simulator (Aspen HYSYS). All the stages are evaluated for their environmental impact using life cycle assessment and various impact parameters such as Global Warming Potential (GWP), Cumulative Primary Energy (CPE), Acidification potential (AP). Eutrophication Potential (EP) and Abiotic Resource Uses (ARU).

Production System - Methodology

System Boundary and Functional Unit.

A system boundary is defined for the biodiesel production system from microalgae considering the main stages and the ancillary processes which include use of fertilizers, transport and the machinery or equipments used. As shown in Fig. 1, the inputs to each stage in terms of material and energy is

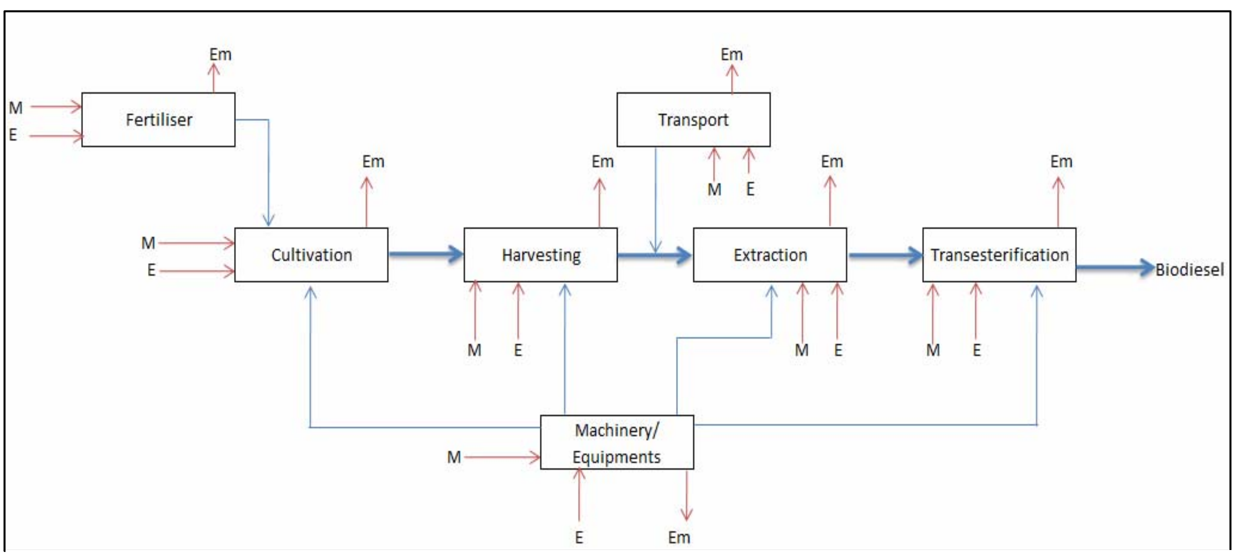

Figure 1: System Boundary for the LCA of biodiesel production process from microalgae.

denoted by M and E respectively while the emissions from each stage are denoted by Em.

The life cycle assessment done is a cradle-to-gate study as the end use of the product is not considered. The functional unit, which is the basis for the LCA is taken as 1 ton of biodiesel produced and all the further calculations are based on this functional unit.

Production System Design.

The species of algae considered for cultivation in this study is *Chlorella sp.* This species has been understood well as considerable amount of work is done on it. The oil content of *Chlorella sp.* is around 10-48%.[9] In this study, oil content is considered to be 40% which is within the feasibility range and also at the higher end of the range which would be aimed for within commercial cultivation. The percentage of dry biomass or the dry mass factor in the cultivation mass is considered to be 5%.

The oil yield from algae production is considered to be 15000 gallons per acre, adopted from the work of Riesing.[18] For 1 ton of biodiesel, a total of 60 ton of algal mass has to be cultivated in the first step with a land requirement of 964 square meters. An oval shaped open pond with a length of 100 m, width of 10 m and depth of 30 cm is considered in this study similar to that considered by Lardon et.al.[13] It is assumed that the land is sufficiently non-porous and there is no need for any lining material. A 750 W pump runs for three hours a day to make up for the loss of water which is considered to be freely available hence neglecting any associated impact factors. The culture medium is kept in constant circulation at a speed of 25 cm/sec. using a paddle wheel which would require a motor of 2 kW.[19]

For cultivation using PBR, flat plate photobioreactors are considered in this study with the length of each flat plate unit being 4.51 m; height, 1 m and the thickness 10 cm, giving a volume of 0.451 m^3. The volume of PBR required for 1 ton of biodiesel production was found out to be 42.25 m^3 considering 0.27 kg/m^3 per day of volumetric productivity.[20] PVC is used as a material of construction (MOC) for PBR with a thickness of 0.005 m, same as that used by Soratana et.al.[21] PVC required for the construction of the total number of units of PBRs was calculated to be 6.25 ton.

The nutrients required in the cultivation stage include CO_2 which is injected in the system. The electricity requirement for CO_2 injection is given in a study by Kadam[22] as 22.2 kWh for 1 ton of CO_2. Other major nutrients required are nitrogen (N), phosphorus (P) and potassium (K). These are supplied through fertilizers. Carbon dioxide requirement for the culture is 1.8 kg per kg of algae grown.[4] Nitrogen required, which is 46 kg/ton of algae is provided by urea while triple superphosphate supplies the 9.9 kg phosphorus and potassium fertiliser is used for 8.2 kg potassium required per ton of algae.[13]

In harvesting the biomass is first separated by natural settling and then is further concentrated using spiral plate centrifugation. Up to 65% of the algal biomass can be collected by natural settling in an hour.[23] The design of settling structure is adapted from the study by Collet et.al.[23] The volume required is calculated to be 15.625 m^3 with a radius of 1.93 m. The length is assumed to be 4 m and concrete is used as the material for construction. Energy required for centrifugation using spiral plate technology is 0.15 MJ/kg algae fed in the system.[23] Steel is used as the material for construction of the centrifuge. Based on the calculations from the study by Collet et.al[23] amount of steel required is found out to be 315.8 kg. Hence the two major materials used in this stage of the process were cement and steel. Other materials which would be required, for example in construction of a facility to house these equipments, were not considered in this study. The emissions from steel and cement production are taken from Bjork et.al[24] and Wu et.al[25] respectively.

The biomass is then further dried using steam. Steam at 10 bar and 176°C (enthalpy, 2.6 MJ/kg) is generated using an industrial boiler which uses natural gas (heating value, 52 MJ/kg) as fuel. Energy required for the drying operation was adopted from the work of Kadam.[22] The emission factors for natural gas burnt in industrial boiler were taken from the Environmental Protection Agency (EPA) document "Compilation of Air Pollutant Emission Factors".

Table 1: Solvent recovery mass/energy data

Solvent recovery mass/energy	Flows
Algae paste available for extraction, in kg	3000
Hexane required per kg of algae paste, in kg[15]	14.74
Total amount of hexane required in kg	44210.53
Amount of hexane recovered, in kg (Assuming 98% hexane from the top can be recovered)	42459.28
Heat required to vaporize this amount of hexane in MJ	3606.92
Mass of steam required at 10 bar and 176 C, in kg	1387.276

Table 1 gives the major flows and the calculated amount of energy required for recovering the solvent. Steam is used for jacket heating. The requirement of total electrical energy is 1.296 MJ per kg of algal paste and is adapted from the study by Harun et.al.[26] The steam for recovery is used at the same conditions as that in the drying operation. The GWP and primary energy data for hexane is taken from the study by Huo et.al.[27] Mechanical extraction does not involve any chemicals and is done using expeller press. A small oil press of capacity to process 30 kg/h of feed is considered with power of 5.5 kW.

The final stage of the process is the transesterification of the algal oil to produce biodiesel. This process and the related operations have been simulated on Aspen HYSYS and the associated mass and energy flows are obtained. The mass flow of oil obtained from the output of the extraction step is 1200 kg. The ratio of MeOH:oil for the reaction, is taken as 6:1.[28] The outlet stream from the reactor is treated in a liquid-liquid extractor to separate biodiesel from the excess methanol, glycerine and the catalyst, which are then recovered in the sequential distillation columns.[29] The biodiesel recovered at the end of the process is found out to be 85% of the feed.

Results – Life Cycle Impact Assessment

The system has been evaluated for prominent impact parameters in each stage. In the cultivation stage, the open pond culture has been compared with photobioreactors and the results are displayed in Table 2.

Table 2: Comparison of environmental impacts for raceway ponds and photobioreactors.

Method	Global Warming (100 years)	Acidification potential, kg SO2 Equiv	Abiotic resource use Sb equ, kg	Photochemical smog (ethylene eq.)
Raceway pond	-3975.40	5.30	9.09	0
PBR	-1980.33	9.43	2.30	0.563

Cultivation is the stage which puts a strong case for use of microalgae as is seen by the negative values for the Global Warming Potential. These negative values are due to the CO_2 consumed in the system during the cultivation of algae.

In the harvesting stage total value for GWP100 is found out to be 4141.5 kg eq. of CO_2 per ton of biodiesel. The contributors in the GWP100 and their percentages are shown in Fig. 2 while Fig. 3, shows the energy consumption and the corresponding CPE demand. In the extraction stage, GWP100 and CPE are compared for both expeller press and solvent extraction using hexane. Use of hexane as a solvent contributes most to the GWP in this stage. As there are no chemicals used in mechanical extraction, the GWP100 is three times smaller than the value in case of chemical extraction. However, the impact of mechanical extraction would be higher if values for MOC of the expeller press and other required material are considered.

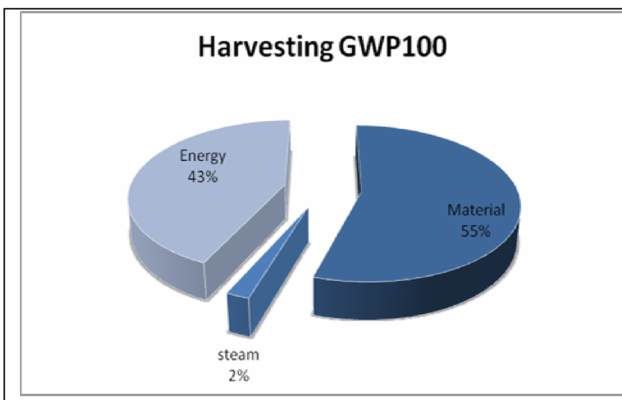

Figure 2: GWP100 contributors in harvesting

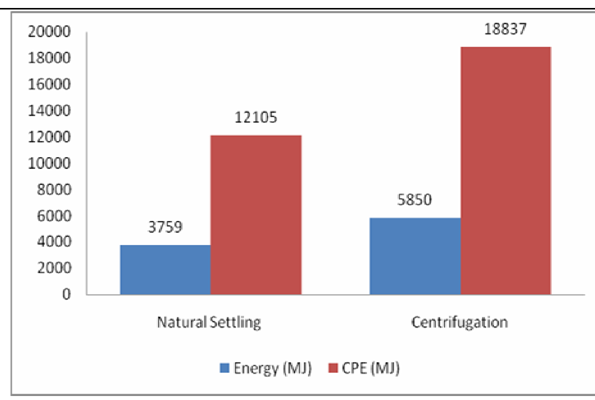

Figure 3: Energy and CPE for harvesting

In the transesterification stage, methanol contributes significantly to the GWP100 and CPE. Power and steam used are the other contributors in this stage. The impact of this stage to the overall GWP100 of the production system is the least compared to the extraction and harvesting stages. The impacts of transport used for the facilitating the process is marginally considered assuming a distance of 50 km. The basic assumption being the entire process occurs in close proximity.

Fig. 4 displays the environmental burdens due to energy used in all the stages. It is evident from the figure that harvesting stage uses the most energy which concurs with most of the literature on algal biodiesel.

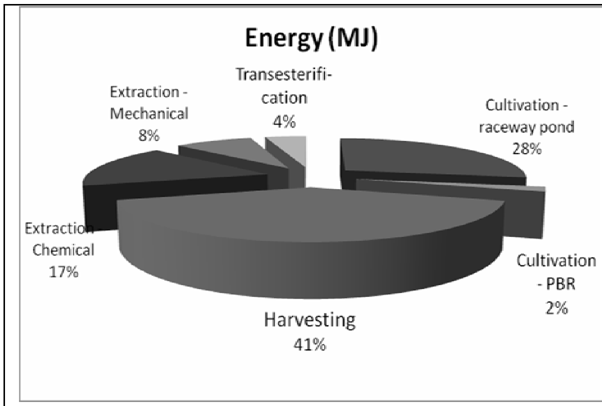

Figure 4: Environmental burdens due to energy

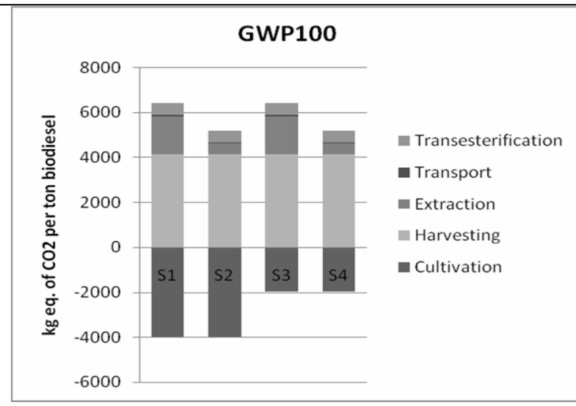

Figure 5: GWP100 for different scenarios

Four different scenarios are compared in this study as shown in Table 3. The results are evaluated for GWP100 which gives kg equivalent of CO_2 per ton of biodiesel produced from the process described. Fig. 5 shows the contribution of different stages in GWP100 for the scenarios compared.

Table 3: Comparison of impact parameters for different scenarios.

Scenario	Cultivation	Extraction	GWP100 kg CO_2 eq./t biodiesel	AP kg SO_2 eq./t of biodiesel	EP kg PO_4^{3-}/t of biodiesel	ARU kg Sb eq./t of biodiesel
S1	Raceway pond	Chemical	2456.161	23.101	29.546	25.303
S2	Raceway pond	Mechanical	124[illegible]	[illegible]	[illegible]	[illegible]
S3	PBR	Chemical	4447.206	27.219	29.552	18.514
S4	PBR	Mechanical	3231.361	26.270	29.550	17.126

GWP100 for scenarios with open pond culture is found out to be much lower than those with photobioreactors. This is primarily due to the contribution of the environmental burdens of MOC used in

PBR. The burdens due to the MOC of equipments used in mechanical extraction have been discounted in this study. Hence the GWP100 for scenarios with mechanical extraction is much lower compared to that of chemical extraction.

A comparison of the values for GWP100 for microalgae-derived biodiesel from different scenarios is done with that of crude-derived diesel. The GWP100 for crude-diesel, 87g CO_2/MJ has been taken from a report by Elsayed et.al.[30] While the net heating value for biodiesel is considered as 37.7 MJ/kg adopted from the same report. The GWP100 for S1 and S2 (61.97 g/MJ and 31.21 g/MJ) are found to be considerably lower than that of crude-diesel. Use of PBR gives much higher value (112.3 g/MJ) while PBR with mechanical extraction gives GWP100 of 81.6 g/MJ. The significantly low values for open pond culture and mechanical extraction indicate that, microalgae derived biodiesel would still have lower GWP than crude-diesel even after adding the environmental burdens not considered in this study.

Conclusion

The Life Cycle Assessment of biodiesel derived from microalgae gives mixed results in terms of the environmental impact when compared with crude-derived diesel. Out of different production scenarios compared in this study, use of open pond culture at the cultivation stage has the least GWP100 value and is lower than that of crude-diesel. However, use of photobioreactors with chemical extraction has a higher value of GWP100. Although while comparing the results from two different LCAs it is necessary to understand the system boundaries considered in the studies, basic requirements for improving a system can be easily identified.

To make the microalgal biodiesel a sustainable technology, effective utilization of the by-products has to be considered as well. Use of MOC with less environmental impact is another area which can be looked into in order to reduce the GWP of PBRs to exploit the advantages they have over open pond culture. New technologies which require less energy need to be explored at the harvesting stage to make the overall process energy efficient. Open pond culture is still attractive when large area of land is available. Algae culture could be an effective CO_2 sequestration technique, not only because it would be cheaper compared to the current technologies being explored but also because it would give valuable renewable fuel like biodiesel.

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