Single Score Life Cycle Optimization of Algae Biodiesel

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Abstract: Environmental concerns and increasing energy demand has pushed many countries to develop alternative energy sources, among which is biofuel. In the Philippines, the Biofuel Act (Republic Act 9367) provides government incentives towards the production of biofuel. Agriculture-based biofuel requires much land and time, while algae-based biofuel would have more potential for mass production considering the high oil yield and shorter harvest cycles. As with any other impact assessment, algae biodiesel production has many facets in its environmental impact. The study focuses on optimizing the single score yield of the life cycle. An integer linear programming model was used in determining the algae biodiesel production pathway with minimized environmental impact. With SimaPro, the environmental impact for each material flow were quantified and assessed to a single score using the EDIP impact assessment method. The model is constrained to produce 10^4 MJ of energy. The results of the study have near similar results to the chosen pathway found in Brentner et al. (2011), with the exception of the harvesting process. The similarity shows the close relationship between environmental impact and energy consumption, particularly on electricity usage. However, the utilization of different chemicals in the harvesting process has yielded a different result. The model used in the study may be further modified to incorporate a wider option of technologies. Future studies may also include the integration of capital investments and financial returns, in order to consider the decisions of stakeholders in implementing the algae biodiesel production design.

Key Words: Microalgae, Life Cycle Optimization, Biodiesel, Single Score, Biofuel

1. INTRODUCTION

Non-renewable resources that are traditionally used for fuels face the issue of limited supply against an ever-increasing demand for energy. Different technologies for energy production processes can emit significant amounts of greenhouse gases into the atmosphere, a well-known one being Carbon

Dioxide (CO_2). Current estimates of CO_2 concentration in the atmosphere have surpassed the safe operating level of the planet (Rockström et al., 2009). Many countries have made policies to further encourage the development of alternative fuel sources. In ASEAN countries, biofuels have been seen as a primary source of renewable energy. The ASEAN countries have implemented their own policies to promote biofuel production (Kumar et al., 2012). In the Philippines, the 'Biofuel Act' (Republic Act 9367) was introduced in 2006 under which The National Biofuel Program was established.

In order to meet with the energy demand and to attain sustainability, there have been attempts to use alternative or renewable energy sources. Biofuels have been suggested as one of the alternatives. Following the Biofuel Act in the Philippines, there were also notably some government incentives towards the production of biofuel such as financial assistance and lesser value added tax. Since these technologies are still comparatively more recent than the non-renewable fuels, many setbacks are still present within their processes. Agriculture based biofuels in particular have problems of inefficient land usage and lengthy harvest time. Were these complications dealt with, algae based biofuels can serve as an alternative. Microalgae have high oil yield per hectare, and application of wastewater as nutrient inputs (Chisti, 2008; Brennan & Owende, 2010). Algae biofuels production are also resilient to atmospheric conditions, as they can be cultivated in a closed system (Searchinger et al., 2008).

Conducting Life Cycle Assessments (LCA) helps in determining the environmental impacts implicated in the production of a product. It assists in providing a comprehensible analysis of the environmental impacts and sustainability of the product. This involves research on the materials used and other details involving the life cycle. With LCA, a comprehensive study on the environmental impacts of algal biofuel production can be done. In a study by Sander and Murthy (2010), LCA was used to study the production of algal biodiesel in terms of energy usage for a functional unit of 1000 MJ. Thermal dewatering was shown to be the most energy intensive, the net CO_2 emission, and other wastes were quantified, thus providing others a basis for further research in more advanced technologies.

Optimization of algal biodiesel production has also been explored by several literatures. In Tan et al. (2014), an Analytical Hierarchy Process was utilized in the optimization of algal biofuel production. Meanwhile, in Rizwan et al. (2015), a superstructure approach was utilized in determining the optimized pathway for algal biofuel production.

In a study by Brentner et al. (2011), the biofuel production process steps were organized into cultivation, harvesting, oil extraction and conversion with various types of technologies considered for each step thereby presenting numerous combinations. A Life Cycle Assessment was conducted in order to determine the pathway with the least energy consumption that can produce 10^4 MJ of energy. Instead of energy as the priority, this study will rather aim to determine the process flow that had the minimum environmental impact in an algae biodiesel production process. This study will have the objective of attaining a single score yield out of the impact assessment of the process flow.

This paper will use the information of the Brentner et al. (2011) study as basis for the different technologies except for Chitosan which was retrieved from Munoz et al. (2017). SimaPro is used as the LCA software, and EcoInvent as the inventory database where the corresponding information with regards to the materials are retrieved. Additionally, the calculations of the single scores are through the EDIP impact assessment method.

2. METHODOLOGY

In this study, an integer linear programming model and Life Cycle Assessment (LCA) is utilized in optimizing the algae biodiesel production. Since there are multiple aspects of environmental effects, the focus will be to optimize the single score yield of the life cycle. The process data used was derived from the study of Brentner et al. (2011). This includes various technologies used in algal biodiesel production with corresponding process flow. The various technologies are grouped into three major processes, namely (1) cultivation, (2) harvesting, and (3) oil extraction and conversion. Fig. 1 shows the flow of the system. In it, the technological alternatives of each process are shown.

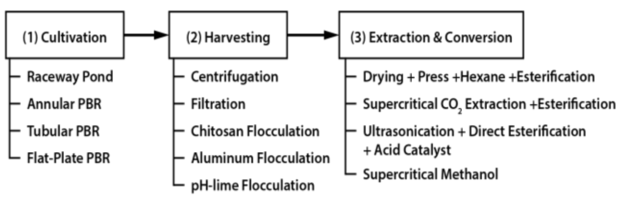

Fig. 1. Process Flow

EcoInvent inventory database provided the emissions linked to the production of each material in the process flow, with the exception of chitosan. The inventory of chitosan was obtained through Muñoz et al. (2017). The production of all materials is assumed to be a reflection of global production as defined by the EcoInvent database, excluding chitosan which reflects only on the production from India (Muñoz et al., 2017).

The environmental impacts were further assessed into a single score using the EDIP impact assessment method. The considered impacts of the impact assessment method are are Global warming, Ozone depletion, Acidification, Eutrophication, Ozone Formation, Human Toxicity, Ecotoxicity, Resource Consumption, and Waste. These impacts are then normalized into a single score through the EDIP methodology. SimaPro was used in obtaining the EcoInvent database and calculating the single score from EDIP.

An integer linear programming model was then used to determine the optimized biofuel pathway with a minimized EDIP single score.

The integer linear programming model is subjected to several equations. In Eq. 1, the technology matrix is composed of the quantities of materials required by each technological option for a given process step. Meanwhile, the scaling vector shows the extent of utilization of the option. The product vector would then indicate the total quantities for each input material of the process. The total quantities for the input materials can then be calculated using Eq. 2.

$$A_i x_i = y_i \quad , \forall_i \qquad \text{(Eq. 1)}$$

where:

i = process step
A = technology matrix
x = scaling vector
y = product vector

$$Y = \sum y_i \qquad \text{(Eq. 2)}$$

where:

i = process step
Y = product vector of system
y = product vector

Afterwards, the total quantities are each scaled by the corresponding single score to yield the environmental impact of each material. As shown in Eq. 3, the transpose of the single score vector is multiplied to obtain the total impact score.

$$B^T Y = z \qquad \text{(Eq. 3)}$$

where:

B = single score vector
Y = product vector of system
z = total impact score

Furthermore, so that the model will only choose one option in each stage, the scaling factors are constrained to binary, as shown in Eq. 4 and 5.

$$x_i \in \{0,1\} \quad , \forall_i \qquad \text{(Eq. 4)}$$
$$\sum x_k = 1 \quad , \forall_i \qquad \text{(Eq. 5)}$$

where:

i = process
k = technological option for process
x = scaling factor

Considering these equations, the total environmental impact is then minimized by the objective function as shown in Eq. 6.

$$min\ z,\ \ f(x_i) = z \qquad \text{(Eq. 6)}$$

where:
i = process
x = scaling factor
z = total impact score

3. RESULTS AND DISCUSSION

Through SimaPro, the single score of each material flow has been quantified. The single score values for each material flow is shown in Table 1. The chosen pathway of the model is to use Flat-Panel PBR for cultivation, pH-Lime Flocculation for harvesting, and Supercritical Methanol for oil extraction and conversion.

Table 1. EDIP Scores of Process Materials

Process	EDIP Score
Aluminum (kg)	3.68×10^{-3}
Chitosan (kg)	4.17×10^{-2}
Concrete (kg)	2.87×10^{-4}
Electricity (kWh)	8.66×10^{-4}
H_3PO_4 (kg)	1.77×10^{-2}
HCl (kg)	3.63×10^{-3}
Heat (MJ)	3.25×10^{-5}
LDPE Sheet (kg)	2.54×10^{-3}
pH-lime (kg)	1.18×10^{-4}
Polycarbonate (kg)	1.04×10^{-2}
Polymethyl Methacrylate (kg)	9.72×10^{-3}
Polypropylene Filter (kg)	2.19×10^{-3}
Steel (kg)	6.61×10^{-3}

The chosen pathway is similar to that of Brenter et al., except that the harvesting opted for the pH-lime flocculation process. The similarity may be attributed to the large effect of electricity consumption which is the connection between minimizing energy consumption and minimizing environmental impact. Even though electricity has a fairly low EDIP score per unit of measurement, it generally has a relatively higher consumption rate as compared to other process materials.

The different flocculation technologies are equally the least energy-intensive harvesting, because of their individual electricity consumption. The higher quantity requirement of pH-lime is outweighed by its much lower impact per quantity. Meanwhile, chitosan has a very high EDIP score which grossly increases its single score. Based from Muñoz et al. (2017), 87.17% of the EDIP score is from the use of sodium hydroxide in the production of chitosan.

In the cultivation process, because of the high impact of electricity consumption, the least energy intensive process was chosen by the optimization algorithm. The fairly high EDIP score of the LDPE sheet was not able to overcome the low electricity consumption due to its low utilization, thus the flat-panel photobioreactor was chosen as the preferred cultivation process. Meanwhile, for the extraction and conversion, supercritical methanol (MeOH) was chosen as it does not consume any electricity. It does however, consume a large amount of heat.

4. CONCLUSIONS

In conclusion, an integer linear programming model was presented that incorporates EDIP single scoring for environmental impacts in algae biodiesel production. The model was able to present a unique pathway in reducing the environmental impact of the algae biodiesel production process. Electricity usage plays a big influence in the total environmental impact, meaning that energy consumption and environmental impact are closely related. It can also be concluded that the differences of the quantities of the materials do not hold as much weight as their impact score as seen in the harvesting process. There are options which have high environmental impacts but would still have potential economic and energy factors which may be investigated by future studies.

In the oil extraction and conversion process, supercritical MeOH was chosen to attain minimum environmental impact. It can be observed that this process consumes large amounts of heat. Therefore, if a scenario occurs in which heat supply is limited, supercritical MeOH may not be opted. Future studies may use this model and introduce a constraint in heat consumption.

Difficulty lies in the inventory database, as this can be a case-to-case basis, particularly the data used for chitosan which was based only on production in India. The model can be modified to fit certain criteria that can satisfy stakeholders of an algal biodiesel plant. Future studies can include a comprehensive inventory flow of each process with additional technological options considered. This paper can serve as basis for future models of optimization studies in terms of environmental impacts. The model can be integrated in an existing model of an algae bioenergy park, such as the one presented by Ubando et al. (2015).

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