Energy and economic analysis of *in situ* biodiesel production from microalgal biomass

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Increasing energy consumption across the globe has gained the researcher's attention to the search for renewable fuels such as biodiesel. The present work focuses on energy and economic analysis of biodiesel synthesis from dried microalgal biomass through *in situ* transesterification (i.e. single stage extraction-transesterification). An entire process has been developed and simulated using Aspen plus V11. Furthermore, mass and energy balances have been investigated. The process is developed assuming the biodiesel plant capacity of ~1500 kg/h. The overall cooling duty and heating duty for the entire process were found to be –6.874 MW and 4.567 MW, respectively. Moreover, the total capital expenditure (CAPEX) and total operating costs (OPEX) were estimated to be $6.534 million and $45.104 million, respectively. Additionally, biodiesel production cost and total outcome was found to be $3.75 per kg and $5.11 per kg respectively. Therefore, net profit was calculated as $1.36 per kg.

Keywords: *In situ* transesterification, process simulation, biodiesel, microalgal biomass, Aspen plus.

Introduction

In recent years, the scarcity of crude petroleum sources and environmental concerns have led to the use of renewable fuels such as biodiesel. The immense increase in fossil fuel consumption has led to an alarming situation[1]. Consequently, several countries such as the United States of America (USA), Brazil, Italy, France, and Malaysia have commenced the industrialization and commercialization of biodiesel production[2]. The conventional method of biodiesel production involves the transesterification of triglycerides into fatty acid methyl esters (FAME), as depicted in Fig. 1. The transesterification reaction can be accomplished using alcohol with or without suitable catalyst[3]. The oil acquired from the food crops such as mustard, sunflower, safflower, soybean, and rapeseed are utilized for biodiesel production. However, route is a major concern worldwide because it eventually causes the food crisis and perturbs the economies. Therefore, the non-edible feedstocks like jatropha, karanja, mahua, rice bran, tobacco seed, rubber seed, waste and
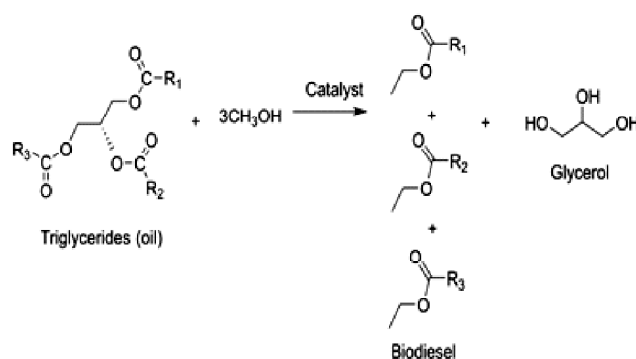

Fig. 1. Transesterification of triglycerides (oil) to biodiesel. R_1, R_2, and R_3 are alkyl groups[8].

animal fats are considered as suitable raw materials for the biodiesel synthesis[4,5]. However, their availability is also uncertain and processing is difficult. On the other hand, the microalgae are unicellular eukaryotes that can grow in any ecosystem on earth and offers several benefits in terms of high biomass productivity, fast growth rate, and high photosynthetic efficiency. Furthermore, it has the highest oil yield

over other traditional terrestrial crops (i.e. 10000 gallons of oil/acre of land)[6]. Hence, the algae biomass is regarded as a potential feedstock for the biodiesel production[7].

A few notable investigations considering the process simulation and economic assessment of biodiesel production from several edible or non-edible oil have been reported[9–14]. A very detailed economic study to produce biodiesel with alkaline catalyst was estimated for a complete entire plant using a commercial process simulator[9]. West *et al.*[10] reported the economy of biodiesel plant producing 8000 ton per year of biodiesel from waste cooking oil (WCO). Four processes using Aspen Hysys were evaluated. These processes are supercritical process, homogeneous alkali-catalyzed process, homogeneous acid-catalyzed process and heterogeneous catalyzed process. The results presented that the heterogeneous catalyzed process was found to be most effective in terms of economics and profitability. In another study Zhang *et al.*[11], reported a technical and economic study on biodiesel synthesis from waste cooking oil using an acid catalyst. Both the process overview and economic analysis were discussed in detail and additional costs were included while Marchetti *et al.*[12] designed and simulated continuous biodiesel plant of capacity 36036 ton/year using Super pro designer. A supercritical transesterification was used to produce biodiesel from waste cooking oil. Three continuous biodiesel production process were simulated by Lee *et al.*[13]. The authors analyzed different processes like alkali catalyzed process and supercritical process. The results showed that the supercritical process was the most profitable overall. Sanchez *et al.*[14] demonstrated the simulation of continuous biodiesel production from microalgal oil with acid catalyst using Aspen Plus simulator 2006.5.

There are no earlier studies on process simulation and economic assessment of biodiesel production from dried microalgae biomass of Chlorella sp. MJ 11/11 has not been yet investigated. Therefore, the present work develops and simulates a biodiesel plant based on the experimental work reported by Ghosh *et al.*[15] to produce biodiesel through *in situ* transesterification process (i.e. single stage extraction-transesterification). Moreover,a steady state process simulation was performed to examine the feasibility of biodiesel production using Aspen plus simulator. Furthermore, in this simulation study, *in situ* transesterification process is repre-sented by a continuous stirred tank reactor (CSTR). In the subsequent part, the effect of important process parameters such as reactor temperature and residence time were investigated. The energy and economic analysis were also carried out in this study.

Process simulation and design

This section describes the methods used to conduct the process simulation and design.

Process simulation:

Aspen plus V11 process simulator was employed to model the homogeneous acid catalyzed *in situ* transesterification of microalgal biomass for biodiesel production. The process developed and simulated in this work is based on the experimental study carried out by Ghosh *et al.*[16] for the biodiesel production through *in situ* process. *In situ* transesterification is represented by a continuous stirred tank reactor (CSTR) and RADFRAC (which performs rigorous equilibrium calculations) columns are used to represent the distillation operations. The steps for accomplishing the process simulation involved specifying: (i) the chemical components for the process and (ii) selection of the thermodynamic property model. Moreover, input and operating conditions, plant capacity and unit operations were also specified.

Chemical components:

The Aspen plus databases have an in-built information for the following components which were utilized in the process: methanol, sulphuric acid, tripalmitin, tristearin, triolein, trilinolein, trilinolenin, methyl palmitate, methyl stearate, methyl oleate, methyl linoleate, methyl linolenate, phenylalanine, sucrose, glycerol, water, calcium oxide and calcium sulphate. Additionally, calcium oxide and calcium sulphate were selected to carry out the neutralization of acid because of their inorganic property.

Thermodynamic model:

The polar nature compounds such as glycerol and methanol were employed in the process. Therefore, the non-random two liquid (NRTL) thermodynamic property model was chosen as the base property method to estimate the activity coefficient of the liquid phase in the simulation[13].

Plant capacity, unit operations and operating conditions:

The plant capacity was assumed to be 1500 kg/h biodiesel

(FAME) synthesis. The required amount of raw materials were calculated based on the Ghosh *et al.*[15]. The amount of microalgal biomass, methanol, sulphuric acid and calcium oxide is 2575 kg/h, 10197.9 kg/h, 2781 kg/h and 1591.3 kg/h respectively. The equipment's employed in the process were: mixer, reactor, component separator, distillation column, pumps, neutralization tank, heater and cooler.

Process design:

The detailed process flow sheet of biodiesel production from dried microalgal biomass is depicted in Fig. 2.

In situ transesterification in a CSTR:

Transesterification involves three moles of alcohol and one mole of oil to form three moles of alkyl esters and one mole of glycerol. Generally, the excess of alcohol drives the reaction towards the products' side. Likewise, alkali, acid or enzyme catalyst can be used to catalyze the transesterification[8].

In situ transesterification is a single-stage process, integrates both oil extraction and transesterification to produce biodiesel. Thus, this method reduces the unit operations such as extraction and purification. Therefore, the equipment requirements, solvent usage, and energy consumption are get decreased. In the present work, *in situ* transesterification process is used for the biodiesel synthesis from dried Chlorella MJ 11/11 microalgae biomass. The microalgae used in this study contained 58% lipids on dry weight basis[16]. The fraction of the remaining components were not mentioned in the base reference. Hence, remaining fraction was equally distributed among carbohydrates and proteins. The dried microalgae biomass was directly charged into the CSTR along with the mixture of methanol and acid catalyst. An acid
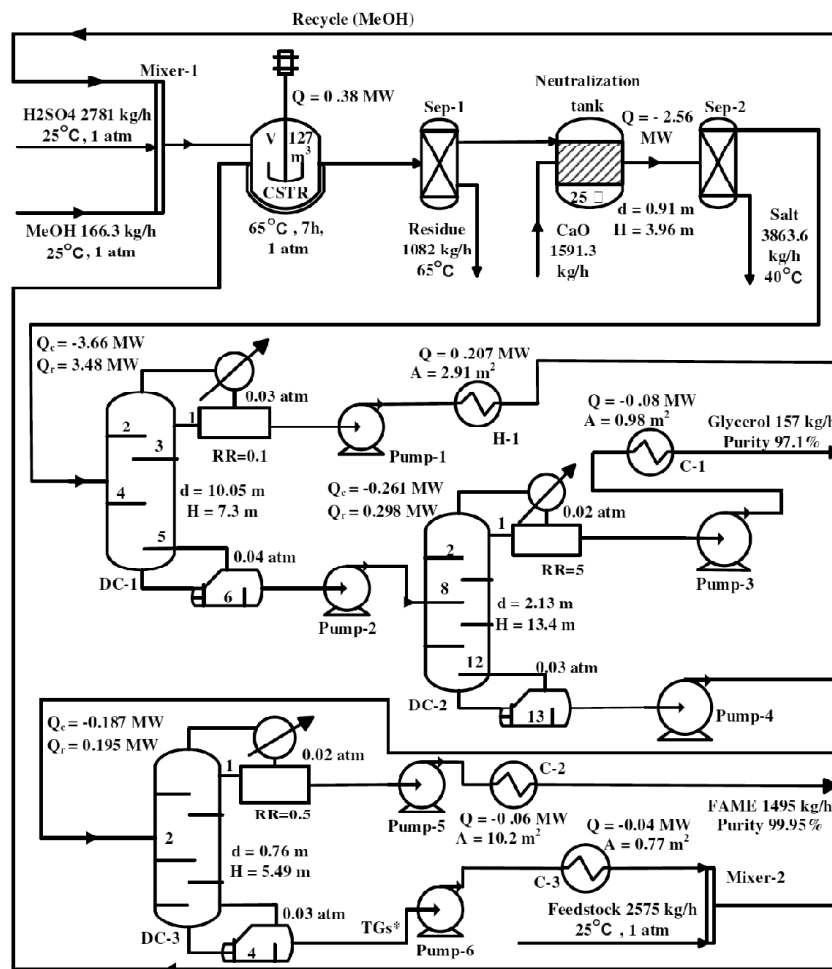

Fig. 2. Schematic process flow diagram of direct biodiesel production from microalgae biomass.

catalyst, i.e. sulphuric acid, was used because microalgal biomass contains high free fatty acids. In this study, excess of methanol was supplied. Methanol also acts as an extracting solvent. The reactor temperature and reaction time were fixed to 65°C and 7 h, as per the study by Ghosh *et al.*[15].

Laboratory scale reaction conditions, such as 1:5 (wt./vol.) algal biomass to methanol ratio, 65°C temperature and 7 h reaction time, were considered as operating conditions in this process[15]. The variation in FAME concentration was measured. A graph between temperature and rate constant (k) was plotted by varying the temperature in the range from 35 to 75°C. A linear plot was obtained, showing first order transesterification reaction. Therefore, it is evident from the results presented in Ghosh *et al.*[15] that the transesterification reaction follows first-order kinetics with frequency factor and activation energy of 3.22 min^{-1} (which was converted to second^{-1} as per the requirement of Aspen Plus software) and 22.828 kJ mol^{-1}, respectively. In this study, the simulation was performed considering the reaction of five triacylglycerols with methanol to produce the corresponding five FAMEs and glycerin. All reactions were assumed to follow the same kinetics. After the biodiesel was produced through *in situ* transesterification reaction, product biodiesel was separated and purified in the downstream. The downstream processing involved residue separation, methanol recovery, catalyst removal, biodiesel purification and glycerin separation.

Catalyst removal:

Calcium oxide (CaO) was supplied to neutralize the acid catalysts that forms calcium sulphate ($CaSO_4$). The reaction for the neutralization is shown below as:

$$CaO + H_2SO_4 \rightarrow CaSO_4 + H_2O$$
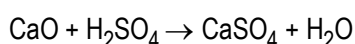
The precipitate (calcium sulphate) was removed using a separator and then the desired product (FAME) and the by-product (glycerol) were separated through a series of distillation columns.

Methanol recovery:

Selected algal biomass to methanol ratio was 1:5 (wt./vol.) which is higher as compared to the stoichiometry of the reaction and therefore the excess methanol must be recycled into the process. This was carried out using a vacuum distillation column to overcome the degradation of biodiesel and glycerol. Methanol is the distillate product with a purity of

100%. The number of stages in the column were chosen based on the required purity and amount of methanol to be distilled while minimizing the reboiler duty. Column with more than six stages and reflux ratio over 0.1 was found to have insignificant effect on methanol purity and recovery. The recovered methanol is heated before being reused and mixed with a fresh stream of methanol prior to entering the reactor. The bottom product comprised of the main mixture of methyl esters, unreacted triglycerides (TGs*), and glycerol at 269 K.

Glycerol separation:

Glycerol is recovered using a distillation column having 13 stages. The feed enters on the eighth tray and a reflux ratio of 5 is specified. The glycerol leaves from the top of the column with 97.11% purity (mass basis) and the bottom stream comprising of FAME and unreacted triglycerides was sent to another distillation column for further separation.

Biodiesel separation:

Biodiesel-glycerol separation is an essential part of biodiesel synthesis. Biodiesel with a high level of glycerol causes several issues such as storage problem, fuel injector clogging and emission of aldehydes[17]. Few studies have been reported for the separation of biodiesel and glycerol mixture by washing with the aid of water[9,10,18] or gravity settling[10,12,19]. It was found by Zhang *et al.*[11] that the desired separation could not be acquired by gravity settling only. Therefore, in this study, biodiesel was separated using a distillation column having four trays. The biodiesel obtained from the top of the column with high purity and unreacted triglycerides in bottom stream was recycled back after cooling down to room temperature.

Results and discussion

Comparison of simulation results:

The simulated process has been validated with previously reported simulation work as well as experimental study. The comparison between the findings of Olivieri *et al.*[20] and the current simulation study is shown in Table 1. These outcomes are in good agreement with each other. However, the wet microalgal biomass was chosen as feedstock by Olivieri *et al.*[20]. Moreover, the present findings match well with the experimental study reported by Ghosh *et al.*[16]. Triglycerides conversion of 93.74% [(wt. of lipids – wt. unreacted lipids/

Table 1. Comparison of simulation results		
Parameters	Results of this work	Results reported[20]
Purity of glycerol (molar%)	98.70	93.92
Purity of FAME (molar%)	98.50	96.80
Conversion of triglycerides (%)	93.77	97.80
Methanol recovery (%)	99.98	92.00

wt.) of lipids] and a biodiesel yield of 54.4% (wt. of FAME/wt. of dry biomass) are obtained in this study, which are consistent with Ghosh *et al.*[15]. Therefore, the modelled *in situ* process for biodiesel production is consistent since its findings are in good agreement with data reported in the literature. Furthermore, sensitivity analysis was performed to analyze the effect of operating parameters such as reaction temperature and reaction time on the process indicators such as biodiesel yield and conversion. An increase in the FAME production was observed when the reaction time was increased beyond 6 h. The reason is being most of the lipids (triglycerides) were already converted in 6 h.

Energy analysis:

Condenser and reboiler heat duties of recovery columns along with the energy consumed in each unit operation are shown in Fig. 3. The methanol recovery column for the recovery of excess methanol has a high condenser and reboiler heat duty as compared to the other recovery columns. This excessive amount of heat duty in the distillation column is mainly due to the large amount of methanol to be recycled. Heat was required to elevate the temperature of distillate product from methanol recovery column so that it could be mixed with fresh stream whereas cooling of main product and by-product, i.e. biodiesel and glycerol were done after
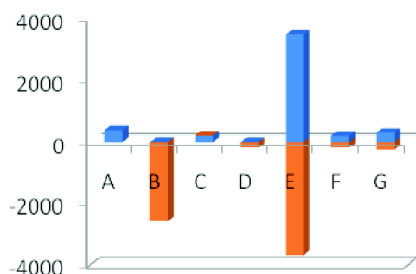

Fig. 3. Energy consumption in each unit [A - CSTR; B - Neutralization tank; C - Heaters; D - Coolers; E - Methanol recovery tower; F - Biodiesel separation tower; G - Glycerol purification tower].

recovery from distillation column. The overall cooling duty and heating duty of this *in situ* process are calculated to be -6.874 MW and 4.567 MW respectively. These duties are relatively small (but significant) as this process considers dried microalgal biomass as a feedstock. Heating duty would be much higher if the energy required for the drying of biomass was to be considered.

Economies of the process:

In general, Lang factor method or bare-module concept was used for the economic estimations[10,11,13]. These concepts reveal an approximate cost estimation and have relatively lower accuracies. Consequently, Aspen in-built economic analyzer was chosen for economic assessment in this work, since it has been employed for over 40 years in commercial plants and process engineering designs, and reveals more accurate cost estimation. Aspen in-built economic analyzer provides economic data and specifications for thorough design and estimation. It allows sensitivity analysis and quick adjustments of the process equipments[13]. Moreover, operating costs, capital costs and the equipments' costs were evaluated using Aspen Economic Analyzer V.11. Fig. 4 shows the share of raw material cost and utility cost in the total operating cost. It can be observed that the cost of raw materials (i.e. dried microalgae and chemicals: ~79%) outweighs the cost of utilities and other costs. Since, the utility cost for the drying of wet microalgae has not been considered in this study and also due to high feedstock cost.
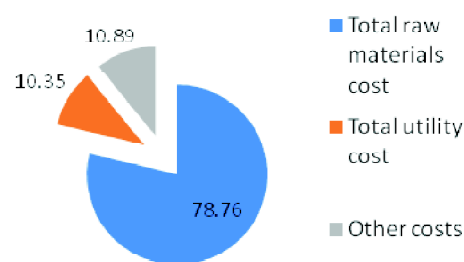

Fig. 4. Share of raw material cost and utility cost in the total operating cost [other costs – labor cost, etc.].

The total capital expenditure, total utility cost, total raw materials cost, total product sales and total operating cost of the process are presented in Table 2. It has been assumed that the plant producing biodiesel will be installed and oper-

Table 2. Economies of the process

Parameters	Values ($)
Total capital cost	6.3049×10^6
Equipment cost	1.7981×10^6
Total installed cost	5.3431×10^6
Total raw materials cost	35.5198×10^6
Total product sales	61.3553×10^6
Total operating cost (annually)	45.1037×10^6
Total utility cost (annually)	4.6683×10^6

times higher than the conventional two-step process. However, the former process is better in terms of processing equipments and kinetics of the reaction. For homogeneous catalyzed *in situ* biodiesel synthesis, Patle *et al.*[28] reported a total module cost of $11.3 million for a plant producing 20 kt biodiesel annually. Patle *et al.*[28] and in the present study same operational time i.e. 8000 h was considered. In the present work, 20.6 kt of dried microalgae biomass was pro-

Table 3. Comparison between a conventional process and *in situ* synthesis process

Authors	Feedstock	Process	Plant capacity (kt per year)	TMC ($ millions)	Product cost ($/kg)
Mohammadshirazi *et al.*[30]	Waste cooking oil	Conventional	2000 L	Not reported	1.06
Patle *et al.*[28]	Wet microalgae biomass	*In situ*	20	11.3	3.13
Heo *et al.*[29]	Wet microalgae biomass	*In situ*	0.48	2.08	7.62
This work	Dry microalgae biomass	*In situ*	12	6.534	3.75

ated in Malaysia. The calculated costs of each parameters and also the price of raw materials is considered in US dollars. The price of biodiesel ($1.464 per kg), methanol ($0.28 per kg), sulphuric acid ($0.4 per kg) and calcium oxide ($0.12 per kg) and biomass ($1.2 per kg) are obtained from previously reported literature[21–24], whereas costs of residue ($0.3 per kg), calcium sulphate ($0.4 per kg), steam ($1.2 per kg) and cooling water ($0.4 per kg) are taken from[25]. Cost of glycerol i.e. $1.1 per kg is taken from[26]. Lastly, price of electricity (i.e. 0.06$ per KWh) is obtained from Lee *et al.*[27]. For the biodiesel production, total operating costs and total product sales were M$ 45.10 and M$ 61.35 respectively. According to the findings of this work, overall biodiesel production cost was $/kg 3.75 and the total income was found out to be $/kg 5.11. Based on these findings net profit was calculated as $/kg 1.36.

Comparison with wet microalgae-based in situ transesterification process:

Recently, Patle *et al.*[28] developed and simulated the *in situ* biodiesel synthesis from wet microalgae using Aspen plus V8.8 simulation package. The feedstock used in this work was wet "*Nannochloropsis* sp." microalgae at a mass flow rate of 50322 kg/h. This microalgae feedstock has 27% lipid content on dry cell weight basis. Based on our research group, Patle *et al.*[28] reported the capital cost of the developed *in situ* biodiesel synthesis process is about 2.5 to 4

cessed and using Aspen economic analyzer, the total capital cost (i.e. a total module cost was found by multiplying the installed cost by 1.18) of $6.534 million is obtained. Patle *et al.*[28] reported a production cost of $3.13 per kg of biodiesel from wet microalgal biomass through *in situ* process. This value is low as compared to the production cost ($3.75/kg) of biodiesel obtained in the present study. These differences in costs are because of the following reasons: type of feedstock, the lipid content of microalgae, amount of chemicals, cost of feedstock, costing procedures and their correlations. Finally, the comparison between various routes producing biodiesel is presented in Table 3. It can be seen from the table that the obtained cost of biodiesel is consistent with the biodiesel costs reported by another researchers[28–30].

Conclusions

In this paper, process development and simulation of the biodiesel production from dried microalgal biomass through *in situ* transesterification with acidic catalyst was performed using Aspen plus V11. From a technical standpoint, this process seems to be viable as it produces a high purity biodiesel product which can be employed in blends with petro-diesel. Consequently, microalgal biodiesel production through *in situ* transesterification method could be commercialized if microalgae strain with high oil content and reactants proportion, co-solvents, catalysts and operating conditions such as temperature, pressure are optimally selected. Furthermore,

the overall cooling duty and heating duty of the entire process were found to be –6.874 MW and 4.567 MW, respectively. Moreover, the total capital investment and total operating costs were calculated to be $6.534 million and $45.104 million, respectively. These numbers denote a significant investment. Moreover, the biodiesel production cost and total outcome was found to be $3.75 per kg and $5.11 per kg respectively. Therefore, net profit was estimated as $1.36 per kg.

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