Accepted Manuscript

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PII: S0960-8524(18)30016-6
DOI: https://doi.org/10.1016/j.biortech.2018.01.016
Reference: BITE 19373

To appear in: *Bioresource Technology*

Received Date: 30 November 2017
Revised Date: 2 January 2018
Accepted Date: 3 January 2018

Please cite this article as: Chen, J., Tyagi, R.D., Li, J., Zhang, X., Drogui, P., Sun, F., Economic assessment of biodiesel production from wastewater sludge, *Bioresource Technology* (2018), doi: https://doi.org/10.1016/j.biortech.2018.01.016

Economic assessment of biodiesel production from wastewater sludge

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Abstract

Currently, there are mainly two pathways of the biodiesel production from wastewater sludge including 1) directly extracting the lipid in sludge and then converting the lipid to biodiesel through trans-esterification, and 2) employing sludge as medium to cultivate oleaginous microorganism to accumulate lipid and then transferring the lipid to biodiesel. So far, the study was still in research stage and its cost feasibility was not yet investigated. In this study, biodiesel production from wastewater sludge was designed and the cost was estimated with SuperPro Designer. With consideration of converting the lipid in raw sludge to biodiesel, the unit production cost was 0.67 US $/kg biodiesel (0.59 US $/L biodiesel). When the sludge was used as medium to grow oleaginous microorganism to accumulate lipid for producing biodiesel, the unit production cost was 1.08 US $/kg biodiesel (0.94 US $/L biodiesel). The study showed that sludge has great potential in biodiesel production.

Keywords: Biodiesel; wastewater sludge; microbial lipid, cost

1. Introduction

Biodiesel as one of the best alternatives of petro-fuel has attracted considerable attention due to the prediction of energy depletion. The current method of biodiesel production is to convert edible oils to biodiesel through trans-esterification (Sajjadi et al., 2016; Sukasem & Manophan, 2017; Yadav et al., 2017). However, the increase of the price of edible oils has hindered the biodiesel production.

Wastewater sludge is naturally produced in large quantity. It was reported that wastewater sludge contained 5 to 20% lipid w/w dry sludge which was comparable to plant seeds (Choi et al., 2014; Kumar et al., 2016; Olkiewicz et al., 2014; Wang et al., 2016). When sludge is used as lipid source, it was expected that the cost of biodiesel production would be highly reduced as sludge was cost free material. In addition, wastewater sludge has been found as a suitable medium to cultivate microorganism due to the fact that the sludge was rich in carbon, nitrogen, and phosphorus (Angerbauer et al., 2008; Ren et al., 2015; Zhang et al., 2014a). Many microorganisms including *Rhodosporidium toruloides*, *Lipomyces starkeyi*, *Trichosporon oleaginosus* have been reported capable of assimilating waste for lipid production (Soccol et al., 2017; Xavier et al., 2017; Zhang et al., 2014b). Therefore, utilization of sludge as medium to cultivate oleaginous microorganism for lipid production could also be an efficient way of reducing the cost of biodiesel production.

Cost is the most concerned item before the product production going to industrial practice. So far, no economic report on sludge for biodiesel production has been released. Computer simulations could provide basic information on the cost feasibility of a process. Work on cost estimation of bio-products such as transglutaminase and butanol with computer simulations has been conducted with success in many industrial processes (Qureshi et al., 2013; Ramirez et al., 2008; Vázquez & Rodríguez, 2011). SuperPro Designer is one of the most frequently utilized simulation programs to model, evaluate and optimize the biotechnology processes (Bajić et al., 2017; Kwiatkowski et al., 2006; Lam et al., 2014; Limonta et al., 2013; Mabrouki et al., 2016).

In this study, processes to produce biodiesel utilization of wastewater sludge as a direct lipid source and cultivation medium to grow oleaginous microorganisms have been designed according to our previous lab study results and the economic analysis of the processes have been performed with SuperPro Designer. The approximate cost of biodiesel production from a commercial scale industry was provided and compared with the current commercial biodiesel production cost to reveal the feasibility of the processes.

2. Materials and methods

2.1. Computing software

In the study, SuperPro Designer was employed to evaluate the cost of the biodiesel production from municipal wastewater sludge.

2.2. Biodiesel production process description

Two processes were investigated in this work: 1) Produce biodiesel from sludge lipid: the wastewater sludge generated in the municipal wastewater treatment plant was directly subjected to organic solvent for lipid extraction, and thereafter the lipid was converted to biodiesel by reacting with methanol in the presence of catalyst; 2) Producing biodiesel from sludge cultivated microorganism: the sludge was used to cultivate oleaginous microorganism after sterilization, the lipid accumulated in the microorganism was then extracted by organic solvent, and then the extracted lipid was transferred to biodiesel under assistance of catalyst. The processes started from the sludge collection till the pure biodiesel was generated.

2.2.1. Produce biodiesel from sludge lipid

The process was designed and showed in Fig. 1. It mainly included the sludge drying, lipid extraction, trans-esterification of the lipid to biodiesel, and biodiesel purification.

In wastewater treatment plant (WWTP), dewatering is normally performed before the sludge is transferred to landfills or for other usages. The dewatered sludge generally has a water content of 20-30%. Study reported that water content had great impact on lipid extraction (Dufreche et al., 2007; Willson et al., 2010); therefore, the first step of the process of producing biodiesel from sludge lipid was the sludge drying to minimize the water effect on lipid extraction (Fig. 1). In the study, rotary dryer with steam as heating agent was selected due to its high efficiency.

After drying, sludge is normally in bulk form. In order to provide a better contact between sludge and lipid extraction solvent (Dufreche et al., 2007; Mondala et al., 2009), grinding was used to reduce the particle size of the sludge from bulk to fine powders. The powdered sludge was then mixed with organic solvents to extract lipid from sludge in extractors. In the extraction, mixture of hexane, acetone, and methanol was used in a ratio of 2:1:1 due to their high lipid recovery efficiency (96%) (Mondala et al., 2009). In our previous study, it was found that wastewater sludge had a lipid content of 9-11% w/w dry matter (Zhang et al., 2014a). Hence, the average value 10% was used in this cost estimation.

After extraction, centrifugation was employed to separate the liquid part (lipid in solvents) from the solid (residual sludge). Te liquid phase was then sent to solvent evaporator to recover the solvents and the residue (lipid) was collected in a storage tank. It was assumed that the solvent loss during the process was 0.5% w/w (Batan L et al., 2010). The recovered solvents were then reused in lipid extraction process after mixed with fresh solvents.

The lipid in the storage tank was then transferred to trans-esterification reactor to synthesis biodiesel with methanol in the presence of sulfide acid (catalyst). Sulfide acid was selected as catalyst due to the high free fatty acid content in the raw sludge lipid (> 5%) (Zhang et al., 2014a). In the reaction, 3 molars methanol reacts with 1 molar lipid to form 3 molars biodiesel and 1 molar glycerol. In order to enhance the reaction shifting to the biodiesel production side, excess methanol is generally added. In the study, methanol to lipid molar ratio used was 6:1 with sulfide acid addition of 5 v/v methanol. The reaction preformed at 50 °C for 12 h to achieve a trans-esterfication efficiency of 99% (Mondala et al., 2009).

After reaction, the mixture (biodiesel, excess methanol, sulfuric acid, by-product glycerol) was first subjected to evaporator to recover the extra methanol which would be then mixed with fresh methanol to synthesize biodiesel in trans-esterification reactor. The remaining mixture was then washed with warm water (50 °C), and allowed for phase separation. The top layer (raw biodiesel) was then distilled to remove the moisture, and finally biodiesel was obtained. The bottom part mainly containing glycerol, sulfide acid and water, was neutralized in neutralization reactor by sodium hydroxide. The heavy part (sodium sulfide) was settled and removed, while the light part (water and glycerol) was distilled to remove water. Glycerol with less than 1% of water was then obtained.

2.2.2. Producing biodiesel from sludge cultivated microorganism

The schematic diagram of the process was showed in Fig. 2. It mainly included the sludge sterilization, oleaginous microorganism cultivation, biomass harvesting, biomass drying, lipid extraction, trans-esterification of the lipid to biodiesel, and biodiesel purification.

According to our previous study, secondary wastewater sludge was more suitable as medium for oleaginous microorganism cultivation due to its higher bioavailability compared to primary wastewater sludge (Zhang et al., 2014a; Zhang et al., 2013). Secondary sludge discharged from sedimentation generally has a solid content of 3% w/v or 30 g/L. In the study, the sludge with suspended solids (SS) concentration of 30 g/L after being sterilized at 121 °C for 15 min was used as medium for lipid accumulation in oleaginous microorganism. The fermentation occurred at 28 °C with 0.5 vvm aeration 200 rpm agitation. According to our lab study, it was assumed that the fermentation broth had a 30 g/L dry matter concentration with lipid content of 40% w/w dry matters after 48 h fermentation (Zhang et al., 2014a; Zhang et al., 2014b).

After fermentation, the sludge-biomass was harvested with centrifugation (Zhang et al., 2013). To further remove water, drying was employed with the same method as described in the section of producing biodiesel from sludge lipid. Thereafter, lipid extraction with chloroform and methanol in 2:1 volume ratio (1 kg of biomass in 4.5 L of solvent mixture) was performed (Zhang et al., 2014b) followed by centrifugation to separate the liquid (lipid in solvent) from the solid (residual sludge-biomass). Then the liquid part was subjected to evaporation to recover solvents from lipid. Similarly as described in the section of producing biodiesel from sludge lipid, it was assumed that the solvent loss during the process was 0.5% w/w (Batan L et al., 2010). The recovered solvents would be then reused for lipid extraction after mixed with fresh solvents. The lipid was sent to form biodiesel.

Biodiesel was synthesized in trans-esterification reactor by reacting with methanol. Unlike biodiesel synthesis from sludge lipid with H_2SO_4 as catalyst, sodium hydroxide was used in biodiesel synthesis from microbial lipid due to its acceptable free fatty acid content (<2%). In the study, methanol to lipid molar ratio 6:1 with 2% NaOH w/w lipid was utilized (Zhang et al., 2014a). The steps following trans-esterification were similar as described in the section of producing biodiesel from sludge lipid.

2.3. Basic information

The simulations were based on 260 tonnes dry sludge utilization per day, which was the sludge production amount in a wastewater treatment plant in Quebec, Canada. It was assumed that the biodiesel production plant was built inside of the wastewater treatment plant which suggested that there was no sludge transportation requirement in the process. The estimation information was summarized in Table 1.

The cost of biodiesel production was mainly contributed by the raw materials, equipment-depended, labor, utilities, laboratory/quality control/quality assurance (lab/QC/QA), and waste treatment/disposal.

Raw materials included the chemicals used in the process such as methanol, catalyst, solvents, etc. The prices of the chemicals were built-in mode.

Equipment-depended was calculated from depreciation, maintenance, and miscellaneous. The depreciation was calculated based on the project life time (10 year in this study). The equipment purchase cost can be estimated from vendor quotations, published data, company data compiled from previous projects, and by using process simulators and other computer aids. Generally, cost data for one or two discrete equipment sizes is available, but the cost for a different size piece of equipment has to be estimated. In such cases, the scaling law can be used as suggested in Eq. 1:

$$Cost2=Cost1\ (size2/size1)^{I} \quad (1)$$

Where the index I value normally falls between 0.5 and 1.0 with an average value for vessels of around 0.6.

Generally 0.6 is applied when I value is unknown (Zhuang et al., 2007). In this study, the equipment cost is from vendor quotations.

Labor cost was based on the local basic labor rate which was 11 US $/h.

Utilities cost was from the consumption of steam, cooling or chilled water, as well as electricity. The amounts were calculated by the program. In terms of unit cost, electricity costs is 0.06 US $/kWh. Heating steam, cooling water, chilled water are 4.2, 0.1, 0.4 US $/1000 kg, respectively.

Lab/QC/QA refers to the cost of off-line analysis, quality control (QC), and quality assurance (QA) costs. This cost is usually 10-20% of the operating labor cost. In this study, the average value 15% was taken to calculated lab/QC/QA cost.

Waste treatment/disposal was separately estimated according to the difference of the wastes (crude glycerol, wastewater, and residual sludge).

3. Results

3.1. Producing biodiesel from sludge lipid

3.1.1. Mass balance

Before the cost estimation, mass balance was performed and presented in Table 2. It can be seen that 260 tonnes of dry sludge could produce 24.71 tonnes of biodiesel, as the plant was designed to convert 260 tonnes of dry sludge per day and the annual operation day was 330, thus the annual biodiesel production was 8154.3 tonnes. Along with biodiesel production, glycerol was simultaneously produced. The glycerol generation rate was 10% of biodiesel, which suggested that 815.4 tonnes glycerol was generated in the biodiesel production process. According to the mass balance, the cost estimation was conducted.

3.1.2. Capital cost

Capital cost is an important factor to direct the decision making of the investors. According to the capital cost, investors can determine whether to invest the project and how to manage the finance. The capital cost was estimated based on the total equipment purchase cost (EPC). The details calculation was shown in Table 3. The total EPC of the process was 1 428 000 US $, and hence, the capital cost was 7 356 000 US $.

3.1.3. Biodiesel production cost

In fact, the production cost of a product is calculated based on the operation cost. The operating cost to run a plant is the sum of all expenses associated with raw materials, equipment, labor, utilities, and lab/QC/QA. Dividing the annual operating cost by the annual production rate yields the unit production cost (in US $/kg).

In the process of biodiesel production from sludge lipid, cost of the raw materials was from the utilization of all chemicals. The price of a raw material can vary widely depending on its required purity. Various raw materials can be found in the Chemical Marketing Reporter. More recently, a number of websites have come online where buyers can find pricing information. In this study, chemical prices were generated by the software. Raw materials included wastewater sludge (lipid source), mixture of hexane: acetone: methanol (solvents), methanol (reactant of trans-esterification), and H_2SO_4 (catalyst), and NaOH (to neutralize H_2SO_4). Sludge was considered as cost free as it was a waste. In the process, solvents after extraction were recovered and reused. However, 0.05% w/w solvent loss was assumed; therefore, it counted for a part of raw material cost. Other chemical cost was calculated based on the amount consumed (Table 8.2). According to the estimation, the raw material cost was 1 494 000 US $/yr.

Labor cost was estimated based on the total number of operators and the operation time (7920 h/yr). In a single product facility, the number of operators in each shift was based on the maximum demand during that shift. In this study, labor cost is calculated by the program with a labor rate of 11 US $/h, and the total labor cost was 779 000 US $/yr. Based on the total labor cost, the cost of lab/QC/QA (=15% of the labor cost) was calculated, which was 117 000 US $/yr.

Utilities included heating (steam) and cooling (cooling or chilled water) utilities as well as electricity. In the simulation, only the electricity consumed by the equipments listed in Fig. 1 was calculated, which was 2 862 920 kWh. However, in fact, the office buildings and the auxiliary equipment also have electricity utilization. The electricity consumption of the unlisted equipment and the general load were assumed to be 5% and 15% of the total electricity utilization of the listed equipment. Thus, electricity cost was estimated to be 206 130 US $. The steam was mainly used in the drying, evaporation, and distillation. Totally, the stream consumption was 337 432 tonnes, and the total cost was 1 417 216 US $. Cooling water and chilled water were used in distillation and solvent recovery process. The required amount of cooling water and chilled water were 111 867 and 373 268 tonnes, respectively, corresponding to 11 187 and 149 307 US $. Thus, the total cost of utilities was 1 783 840 US $.

Equipment-dependent is from the depreciation of the fixed capital investment, maintenance of equipment, insurance, and local (property) taxes. For preliminary cost estimates, the entire fixed capital investment was usually depreciated linearly over a 10-year period. The annual equipment maintenance cost was normally estimated as a 10% of the equipment’s purchase cost (Petrides, 2015). Insurance value for bio-processing facilities was generally in the range of 0.5-1% of direct fixed capital (DFC). In this study 1% DFC was taken for insurance cost. The local tax was usually 2-5% of DFC and 2% was taken in this study. The factory expense represented overhead cost incurred by the operation of non-process-oriented facilities and organizations including accounting, payroll, fire protection, security, cafeteria, etc. A value of 5-10% of DFC was appropriate for these costs and 5% was taken in this study. Thus, it was obtained that the equipment-dependent was 1 296 000 US $/yr.

Wastes generated in the process were mainly crude glycerol and the residual sludge. In the process, crude glycerol was purified to pure glycerol, thus it was considered no cost in the crude glycerol treatment. In addition, crude glycerol was not a waste and had value in the market (0.1-

0.5 US $/kg). The residual sludge after lipid extraction was assumed to disposal in landfill. In fact, the sludge was sent to landfill if it wasn't utilized for lipid extraction and biodiesel production. Utilization of sludge for biodiesel production had reduced the cost of sludge disposal, and hence the residual sludge was not considered as the waste generated in the process. Therefore, it was assumed that there was no cost generated in waste disposal.

By sum of the raw material, labor, utilities, lab/QC/QA, and equipment-dependent cost, the total of annul operation cost was 5 469 840 US $/yr with biodiesel production rate of 8154.3 tonnes/yr. The detailed cost of the process (raw materials, equipment, labor, lab/QC/QA, and utilization) was shown in Table 4. The unit biodiesel production cost (annul operation cost by annul production rate) was then estimated to be 0.67 US $/kg (0.59 $/L with biodiesel density 0.88 kg/L).

3.1.4. Credits

Glycerol was produced as by-product along with biodiesel in the process. Glycerol has great value in pharmaceutical industries, thus it was considered that there was credits from the glycerol generated in the process. The current glycerol price was around 0.50-1.00 US $/kg. In this study, it was assumed that the glycerol price was 0.50 US $/kg, and thus the credit from the production of glycerol (0.1 kg glycerol/kg biodiesel) was 0.05 US $/kg biodiesel. Additionally, due to the biodiesel production, sludge volume was reduced from per 260 tonnes to 235.29 tonnes. It suggested that sludge disposal volume was reduced and hence the disposal fee was saved when residual sludge was considered to be sent for landfilling. Therefore, the avoidance of the reduced volume sludge could be considered as credit (0.97 cent/kg biodiesel) (Wheeler et al. 2008). The general cost of sludge landfill was 110 US $/tonne sludge. Thus, the credit from the prevention of sludge landfill was 0.11 US $/kg biodiesel. After taken credits from glycerol generation and sludge disposal, the net unit biodiesel production was 0.53 US $/kg (0.47 US $/L).

The biodiesel production cost was 0.67 US $/kg (0.59 US $/L) when sludge was directly utilized as lipid source before taking credit. It was mainly due to the consumption of raw materials and utilities and the cost spent in equipment, lab/QC/QA, and labor. The cost fraction of the raw materials, utilities, equipment, labor and lab/QC/QA was 27.31%, 32.61%, 23.70%, 14.24% and 2.14%, respectively. It implied that the greatest contributor to the final cost was utilities followed by raw materials. It was different from other studies which reported that the cost was mainly from the raw materials (up to 50-70% of the total cost) (Madani et al., 2017; Patel et al., 2017; Živković et al., 2017). It would be due to that the lipid source in the study was wastewater sludge which was cost free. The study showed that the cost of biodiesel produced from the oil contained in sludge (0.67 US $/kg biodiesel) was competitive with that from soybean which was 0.92 US $/kg biodiesel (Patel et al., 2017).

3.2. Producing biodiesel from sludge cultivated microorganism

3.2.1. Mass balance

The SS concentration of the sludge collected from secondary sedimentation was around 30 g/L, which was found suitable for lipid accumulation (Zhang et al., 2014a). Therefore, the sludge discharged from the secondary sedimentation tank was directly used as medium for oleaginous microorganism after sterilization. The sludge utilization amount was 260 tonnes per day in dry sludge basis, and 90% of the sludge was used as fermentation medium with the rest of that (10%) as seed culture medium. The mass balance of the process was shown in Table 5.

The 260 tonnes of sludge could produce 98.84 tonnes of biodiesel, which suggested that the annual biodiesel production was 32617.73 tonnes with the annual operation days of 330. The 3261.77 tonnes glycerol as by-product was simultaneously generated. Based on the mass balance calculation, the cost estimation was performed.

3.2.2. Capital cost

Capital cost was estimated with the similar method as the process of producing biodiesel from sludge lipid (Table 3). The capital cost was 59 259 000 US $ according to the total EPC of 11 136 000 US $.

3.2.3. Biodiesel production cost

Similarly as the process of producing biodiesel from sludge lipid, the operating cost was estimated based on the cost of raw materials, equipment, labor, utilities, and lab/QC/QA. The unit biodiesel production cost (in US $/kg) was obtained by dividing the annual operating cost with the annual production rate.

In the process of biodiesel production from the lipid accumulated in microorganism cultivated with sludge, the raw material cost was due to the utilization of the chloroform, methanol, NaOH, and HCl (Table 5). Among all, chloroform and methanol (the part as solvent employed in the extraction) was recovered but with a 0.5% w/w loss. The prices of these chemicals were generated by the program. The total cost from the raw material utilization was 6 026 000 US $/yr. The labor cost was similar estimated as the biodiesel production from sludge lipid, which was 2 256 000 US $/yr, accordingly, the cost due to the lab/QC/QA was obtained to be 338 400 US $/yr. The utilities cost was due to the consumption of steam, cooling or chilled water, and electricity. Similar calculations were performed as the biodiesel production from sludge lipid. It showed that the total cost of the utilities was 15 693 000 US $/yr. The equipment-dependent cost was 10 494 000 US $/yr. Waste generated was the wastewater generated during centrifugation. The cost to treat the wastewater was around 0.42 US $/m^3 (general treatment + tertiary treatment) and around 0.20 US$/m^3 with and without considering the wastewater reuse, respectively (Li et al., 2017; Ruiz-Rosa et al., 2016). In this study, 0.20 US $/m^3 was adopted for the wastewater treatment cost. The generated wastewater was 2 431 001 m^3/yr (Table 5: 7366.67 tonnes/d). It suggested that 486 200 US $ cost would occur in the waste treatment.

The total annual operation cost (Σ raw material, labor, utilities, lab/QC/QA, equipment-dependent cost, and waste treatment) was 35 293 600 US $. The annual biodiesel production rate was 32617.73 tonnes. Hence, the unit biodiesel production cost was calculated to be 1.08 US $/kg (0.94 US $/L with biodiesel density 0.88 kg/L).

3.2.4. Credits

As mentioned, the glycerol could compensate some part of the biodiesel production cost. It assumed that the credit from the glycerol (0.1 kg glycerol/kg biodiesel) was 0.05 US $/kg biodiesel.

As sludge was used to cultivate the oleaginous microorganisms, it was converted to microorganism biomass. The lipid content of the biomass was assumed to be 40%. It suggested that around 60% of the biomass would be left after lipid extraction and required to landfill. However, the sludge landfill amount was reduced from 260 tonnes to 160.16 tonnes due to the lipid generation. Consequently, the sludge disposal fee was saved. As mentioned, the credit taken due to the prevention of sludge landfill was 0.11 US $/kg biodiesel. The total credits would be

0.16 US $/kg biodiesel (=0.05 US $/kg biodiesel from glycerol and 0.11 US $/kg from the avoidance of sludge disposal). It indicates that the net unit biodiesel production was 0.92 US $/kg (0.78 US $/L).

4. Discussion

The capital cost of the process of the biodiesel production from the lipid accumulated in the microorganism cultivated with sludge was 59 259 000 US $, which was 7 356 000 US $ for the process of the biodiesel produce from the lipid directly extracted from the sludge. It indicated that the investment would be almost 7 times higher in the former case than that of the latter. This would be the main obstacle of the application of the sludge as medium of oleaginous microorganism for biodiesel production.

In addition, without taking credit, the biodiesel production cost was 1.08 US $/kg (0.94 US $/L) with 17.07% from raw materials, 30.73% from equipment, 6.39% from labor, 0.96% from lab/QC/QA, 44.47% from utilities, and 1.38% from waste treatment. The cost was higher than the commercial biodiesel derived from soybean which was 0.92 US $/kg biodiesel (Patel et al., 2017). Compared to the biodiesel produce from the lipid directly extracted from the sludge (0.67 US $/kg biodiesel), the cost of biodiesel production from the lipid accumulated in the microorganism cultivated with sludge was higher. It was mainly due to the fermentation which was not required in the biodiesel produce from the lipid directly extracted from the sludge. The requirement of the fermentation involved the additional equipment purchase (fermenters and centrifuges), labor input, utilities consumption (sterilization, agitation and aeration during fermentation, centrifugation), and waste treatment. Thus, the cost was more even though more biodiesel was produced in the biodiesel production from the lipid accumulated in the microorganism cultivated with sludge than in the biodiesel produce from the lipid directly extracted from the sludge. However, it could be seen that the sludge reduction amount was 3 times higher in the biodiesel produced from sludge cultivated oleaginous microorganism (the residual sludge amount was 160.16 tonnes from every 260 tonnes) than in the biodiesel produced directly from sludge contained lipid (the residual sludge amount was 235.29 tonnes from every 260 tonnes).

To make the biodiesel production from the lipid accumulated in the microorganism cultivated with sludge being competitive with the biodiesel produced from the lipid directly extracted from the sludge, the fermentation has to be simplified. The sterilization (121 °C for 15 min) should be avoided as it was a high energy consumption process. When the fermentation could be performed without the requirement of sterilization, the cost could be reduced to 0.91 US $/kg biodiesel from 1.08 US $/kg biodiesel, which was cheaper than the biodiesel produced from soybean oil (0.92 US $/kg biodiesel). In addition, the cost could be also reduced if the lipid content could be further increased from 40% to higher, correspondingly the lipid productivity increased from 6 g/L/d to higher. When the lipid content increased from 40% (lipid productivities 6 g/L/d) to 50% (lipid productivities 7.5 g/L/d) or 60% (lipid productivities 9 g/L/d) the biodiesel production cost could be reduced from 1.08 US $/kg (0.94 US $/L) to 0.86 US $/kg (0.75 US $/L) or 0.71 US $/kg (0.63US $/L), respectively. It indicates that the lipid productivity has great impact on biodiesel production cost. With the increase of lipid productivity, the cost of biodiesel production from sludge cultivated microorganism could be highly reduced. Moreover, the cost could be further reduced when the residual biomass (obtained after lipid extraction) was used as fertilizers as it could be considered as credit of the biodiesel production.

In this study, it was assumed that the lipid was extracted from dry sludge or biomass which was similar as plant seed oil extraction occurred at dry basis. In fact, lipid extraction from wet biomass has been reported to be as efficient as the extraction from dry ones (Park et al., 2015a; Shankar et al., 2017). Additionally, *in-situ* trans-esterification of dry or wet biomass directly to biodiesel without the separately lipid extraction step have also been widely investigated, and the conversion efficiency of lipid to biodiesel was up to 95% which was similar as the two step trans-esterification (lipid extraction + trans-esterification) (Park et al., 2015b; Park et al., 2017; Song et al., 2016). When the lipid extraction could be accomplished from wet biomass or biodiesel production through *in-situ* trans-esterification, it was expected that the biodiesel production cost could be further reduced in both the cases (producing biodiesel from sludge lipid and sludge cultivated microbial lipid to biodiesel).

In this study, the plant scale impact on the biodiesel production cost has been investigated. It was observed that the production cost was decreased from 1.48 to 0.81 US $/kg biodiesel with the plant scale increase from processing 80 to 440 tonnes per day (biodiesel cost 1.47 US $/kg at 80 tonnes sludge per day, 1.26 US $/kg at 170 tonnes sludge per day, 1.08 US $/kg at 260 tonnes sludge per day, 0.93 US $/kg at 350 tonnes sludge per day, 0.82 US $/kg 440 tonnes per day, respectively), in the case of employing sludge as medium to produce microbial lipid which was then transferred to biodiesel. It was obvious that the biodiesel production cost declined with the increase of plant scale when other parameters (biomass yield from sludge, lipid content in the biomass, lipid extraction efficiency, and lipid trans-esterification efficiency) were fixed. The biodiesel production cost was contributed by the utilization of raw materials, equipment-depended, the employment of labor, the lab/QC/QA, and the consumption of utilities and their weigh in the unit production cost was shown in Fig. 3. Raw material utilization was determined by the biodiesel yield from sludge. It suggested that the cost from raw materials was fixed as long as the productivity of biodiesel (determined by the biomass and lipid yield from sludge) didn't change. Hence, the cost from raw materials was constant with plant scale increase when kept other parameters unchanged. The labor cost just slightly increased with the increase of plant scale as the labor duty didn't have great difference in the large scale and small scale. The lab/QC/QA (15% of the labor cost) was estimated based on the labor cost, thus no much change was observed. Among all, the equipment-dependent and utilities consumption led to the major variation on the cost. The equipment size and amount of utilities demanded were changed as the plant scale changed, and hence the cost was impacted with the variation of plant scale. Though the unit biodiesel production cost decreased with the increase of the plant scale, the capital cost was elevated with the increase of the plant scale. The investment ability has to be considered before start up a plant but not only the unit production cost of the biodiesel.

5. Conclusions

The cost of biodiesel produced from the lipid extracted from sludge was lower than that from soybean oil. It revealed that there was great potential of utilization of sludge lipid for biodiesel production. The cost of biodiesel produced from sludge cultivated microorganism was uncompetitive with the soybean oil biodiesel (commercial biodiesel); however, this study found that the cost could be acceptable when sterilization was avoided. Direct fermenting of sludge for lipid production followed by conversion of the lipid to biodiesel was highly demanded as it could provide high sludge reduction amount as well as competitive cost as commercial biodiesel.

Acknowledgements

Sincere thanks are due to the grants No. 2016YFE0123400 from the Program of International S&T Cooperation, No. FG45001003 from start-up funding provided by HITSZ, and the Natural Sciences and Engineering Research Council of Canada (Grant A 4984, Canada Research Chair) for their financial support.

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Table 1. Basic information of the study

Items	Description
Capacity	260 tonnes dry sludge per day
Plant location	Near wastewater sludge treatment
Construction period	30 months
Project life time	10 years
Production level in the 10 years	100%
Income tax	30%
The plant operation hour	7920 h
Equipment price	Obtained from manufacturer
Chemical price	Built-in mode
Labor	11.00 US $/h
Electricity	0.06 US $/kWh
Steam	4.20 US $/tonne
Cooling water	0.10 US $/tonne
Chilled water	0.40 US $/tonne

Table 2. Mass balance of biodiesel production from raw sludge lipid

Process	Component	Input (tonne/d)	Output (tonne/d)
Sludge drying	Sludge (3% w/v)	8 666.67	0
	Water	0	8 406.67
	Dry sludge	0	260
	Total	8 666.67	8 666.67
Grinding	Bulk dry sludge	260	0
	Powdered dry sludge	0	260
	Total	260	260
Extraction	Powdered dry sludge	260	0
	Hexane	954.2	0
	Acetone	494	0
	Methanol	494	0
	Mixture 1 (solvent phase)	0	1 967.16
	Solid phase	0	235.04
	Total	2 202.2	2202.2
Evaporation	Mixture 1	1 967.16	0
	Lipid	0	24.96
	Recovered solvents	0	1 932.49
	Loss of solvents	0	9.71
	Total	1 967.16	1 967.16
Trans-esterification	Lipids	24.96	0
	Methanol	5.29	0
	H_2SO_4	0.41	0
	Mixture 2	0	30.66
	Total	30.66	30.66
Methanol recovery	Mixture 2	30.66	0

	Methanol recovered	0	2.64
	Mixture 3	0	28.02
	Total	30.66	30.66
Water washing	Mixture 3	28.02	0
	Water (50 °C)	0.03	0
	Diluted mixture 3	0	28.05
	Total	28.05	28.05
Phase separation	Diluted mixture 3	28.05	0
	Mixture 4 (raw biodiesel)	0	24.72
	Mixture 5 (crude glycerol)	0	3.33
	Total	28.05	28.05
Biodiesel drying	Mixture 4	24.72	0
	Biodiesel	0	24.71
	Water	0	0.01
	Total	24.72	24.72
Glycerol purification	Mixture 6	3.33	0
	NaOH	0.35	0
	Glycerol	0	2.47
	Salt	0	0.44
	Water	0	0.77
	Total	3.68	3.68

Table 3. Calculation information of capital investment

Items	Values
Depreciation	15 years
Salvage	5%
Total plant direct cost (TPDC)	
Equipment Purchase Cost (EPC)	From references
Installation	0.40 x EPC
Process Piping	0.35 x EPC
Instrumentation	0.40 x EPC
Insulation	0.03 x EPC
Electrical Facilities	0.1 x EPC
Unlisted equipment purchase cost (UEPC)	0.20 x EPC
Unlisted equipment installation	0.35 x UEPC
TOTAL PLANT INDIRECT COST (TPIC)	
Engineering	0.25 x TPDC
TOTAL PLANT COST (TPC)	TPDC+TPIC
Contractor's fee	0.05 x TPC
Contingency	0.10 x TPC
Direct fixed capital (DFC)	TPC+ Contractor's fee+ Contingency
Startup and validation cost	5% DFC
Maintenance	1% DFC
Insurance	1% DFC
Local taxes	2% DFC
Factory expense	5% DFC

Table 4. The detailed cost report of biodiesel production from raw sludge lipid

Item	Name	Cost ($/yr)	Fraction
Raw materials	Reactant (Methanol); Lost solvent (Hexane, Acetone, methanol); Catalyst (Sulfuric acid); Neutralizer (Sodium hydroxide); Lipid source (sludge: zero cost)	1 494 000	27.31%
Equipment	Dryer; conveyor; grinder; extractor; evaporator, storage tank; trans-esterification reactor; mixer; centrifuge; distillation columns	1 296 000	23.70%
Labor	70819 hours per year	779 000	14.24%
Lab/QC/QA	Laboratory/quality control/quality assurance	117 000	2.14%
Utilities	Electricity; steam; cooling water; chilled water	1 738 840	32.61%
Total		5 469 840	100.00%
Unit biodiesel cost	Biodiesel production rate 8154.3 tonnes/yr	0.67 $/kg (0.59 $/L)	

Table 5. Mass balance of biodiesel production from sludge cultivated microorganism

Process	Component	Input (tonne/d)	Output (tonne/d)
Sludge sterilization	Sludge (30 g/L)	8 666.67	8 666.67
Fermentation	Sludge medium (SS 30 g/L)	7800.00	0.00
	Seed	866.67	0.00
	Fermentation broth	0.00	8 666.67
	Total	8 666.67	8 666.67
Centrifugation (biomass harvesting)	Fermentation broth	8 666.67	0.00
	Water	0.00	7366.67
	Wet biomass (80% water content)	0.00	1300.00
	Total	8 666.67	8 666.67
Biomass drying	Wet biomass (80% water content)	1300.00	0.00
	Dry biomass	0.00	260.00
	Water vapor	0.00	1040.00
	Total	1300.00	1300.00
Extraction	Powdered dry sludge	260	0
	Chloroform	1157.52	0
	Methanol	308.10	0
	Mixture 1 (solvent phase)	0	1565.46
	Solid phase	0	160.16
	Total	1725.62	1725.62
Evaporation	Mixture 1	1565.46	0
	Lipid	0	99.84
	Recovered solvents	0	1458.29
	Loss of solvents	0	7.33
	Total	1565.46	1565.46
Trans-esterification	Lipids	99.84	0
	Methanol	21.16	0
	NaOH	2.00	0
	Mixture 2	0	123.00
	Total	123.00	123.00
Methanol recovery	Mixture 2	123.00	0
	Methanol recovered	0	10.58
	Mixture 3	0	112.42
	Total	123.00	123.00
Water washing	Mixture 3	112.42	0
	Water (50 °C)	0.12	0
	Mixture 4	0	112.54
	Total	112.54	112.54
Phase separation	Mixture 4	112.54	0
	Raw biodiesel	0	98.88
	Mixture 5	0	13.66
	Total	112.54	112.54

Biodiesel drying	Raw biodiesel	98.88	0
	Biodiesel	0	98.84
	Water	0	0.04
	Total	98.88	98.88
Glycerol purification	Mixture 5	13.66	0
	HCl	1.82	0
	Glycerol	0	9.88
	Salt	0	2.93
	Water	0	2.67
	Total	15.48	15.48

Table 6. The detailed cost report of biodiesel production from lipid extracted from microorganism cultivated with sludge

Item	Name	Cost (US $/yr)	Fraction
Raw materials	Reactant (Methanol); Lost solvent (chloroform, methanol); Catalyst (sodium hydroxide); Neutralizer (HCl); Nutrient medium (sludge: zero cost)	6 026 000	17.07%
Equipment	Dryer; conveyor; grinder; extractor; evaporator, storage tank; trans-esterification reactor; mixer; centrifuge; distillation columns	10 494 000	30.73%
Labor	205091 hours per year	2 256 000	6.39%
Lab/QC/QA	Laboratory/quality control/quality assurance	338 400	0.96%
Utilities	Electricity; steam; cooling water; chilled water	15 693 000	44.47%
Waste treatment	To treat the wastewater generated after fermentation	486 200	1.38%
Total		35 293 600	100.00%
Unit biodiesel cost	Biodiesel production rate 32617.73 tonnes/yr	1.08 US $/kg (0.94 US $/L)	

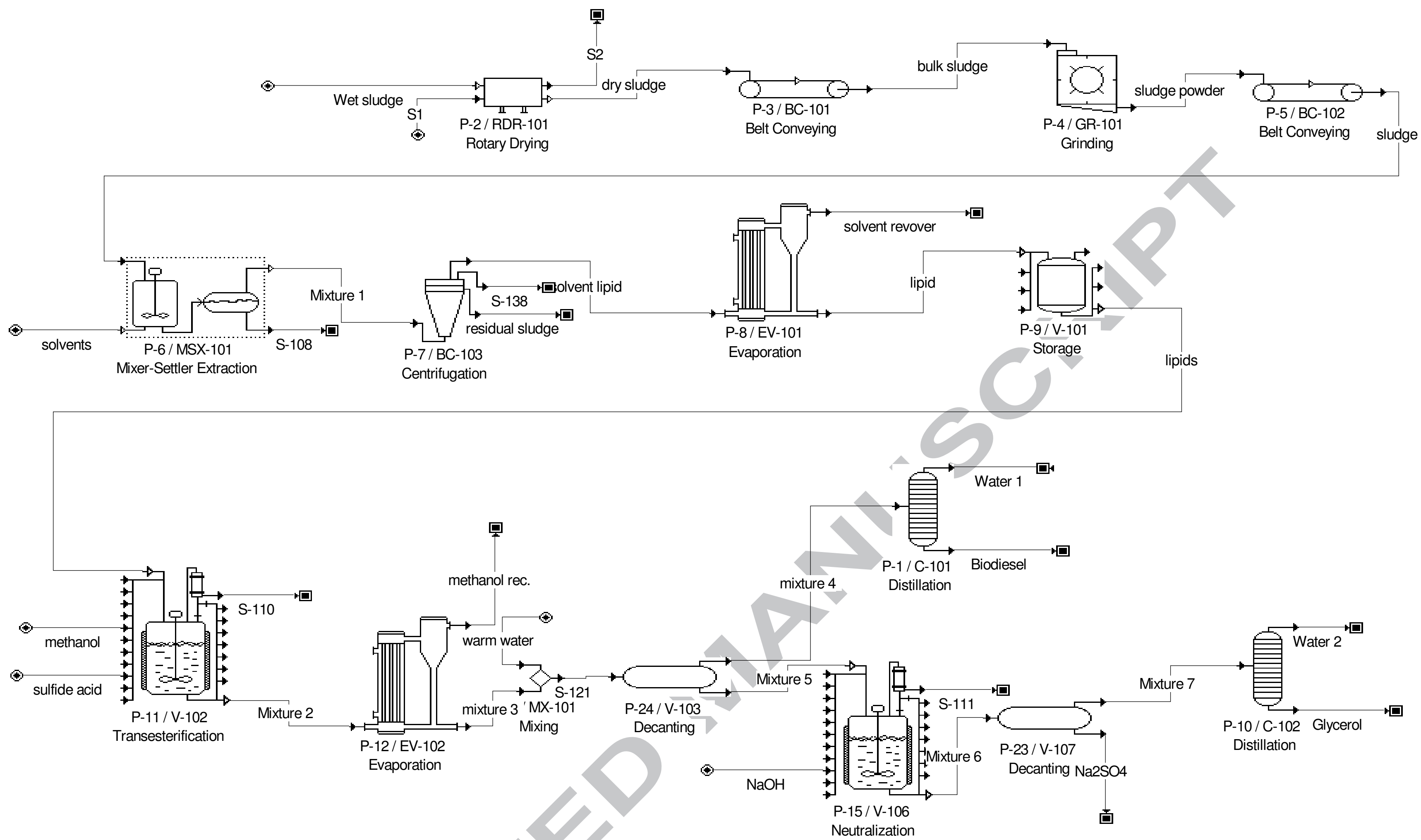

Fig.1 Biodiesel production from sludge lipid

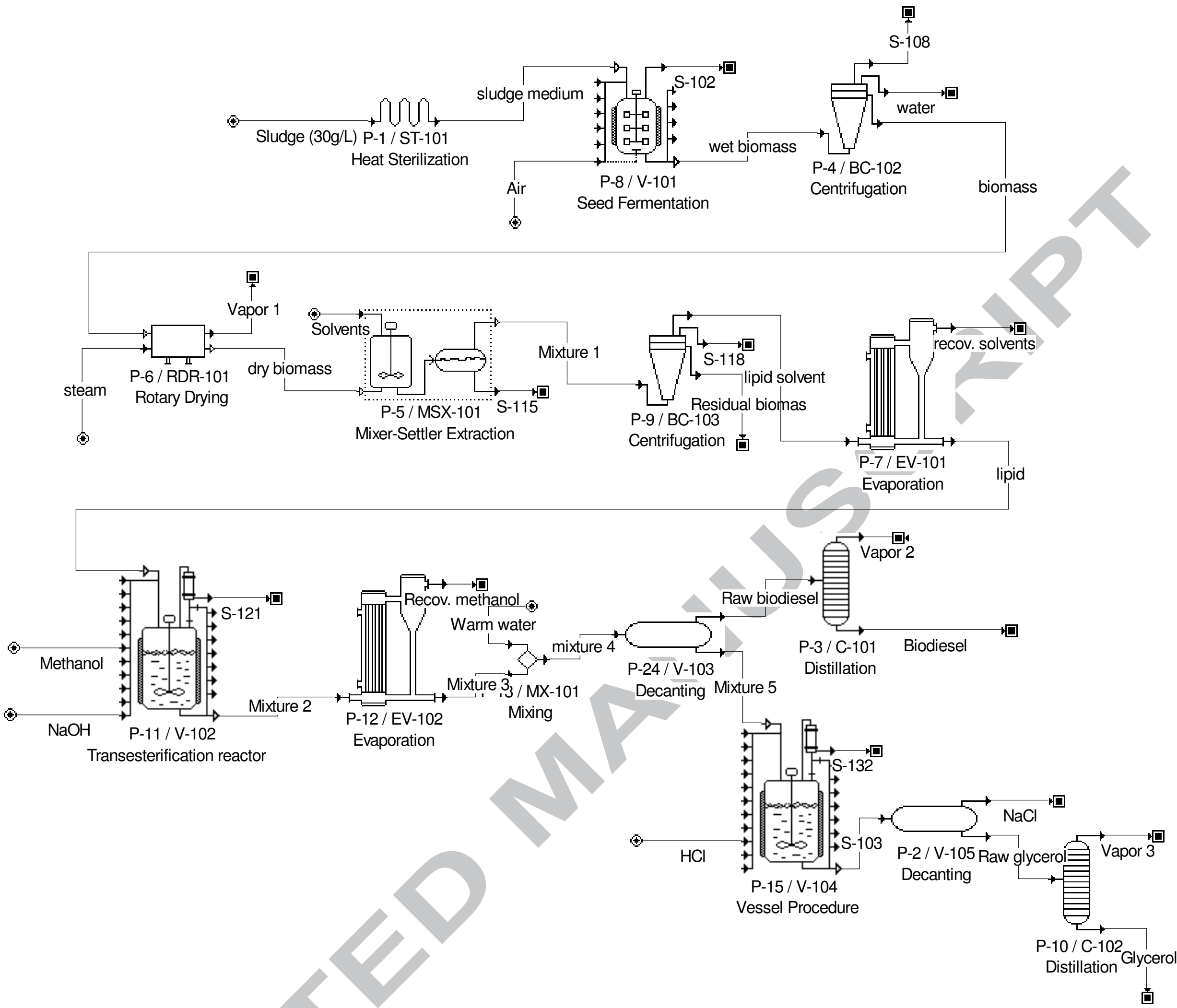

Fig. 2 Biodiesel production from lipid accumulated in microorganism cultivated with sludge

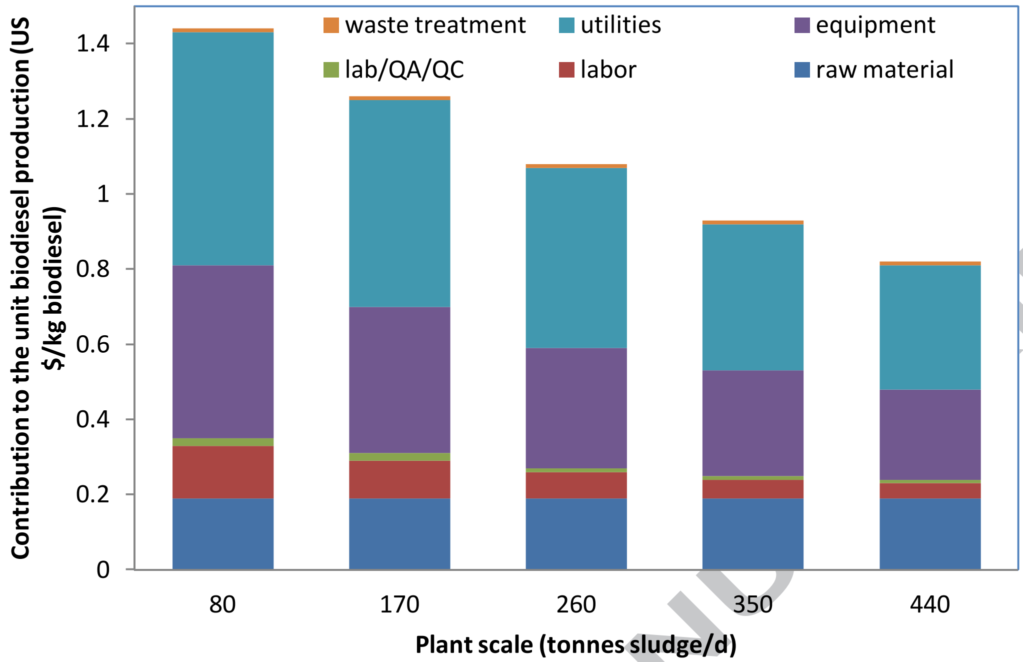

Fig. 3 The contributors of the unit biodiesel production cost

1. The cost of biodiesel from sludge was in the range of 0.67-1.07 US $/kg biodiesel.

2. Utilization of the lipid containing in sludge for biodiesel production was cost favourable.

3. Plant scale and lipid productivity have great impact on the biodiesel production cost.