Chapter 7
The Bioeconomy of Microalgal Biofuels

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Abstract Biofuels such as biodiesel and bioethanol, synthesized via microalgal bioprocess engineering, could be a major contributor to the purview of sustainable energy in the foreseeable future. In contrast to other biomass feedstocks like corn, sugar crops, and vegetable oil, microalgae display a number of significantly superior benefits as a raw material for biofuel manufacturing. This includes an enhanced metabolic rate of biomass production, subsistence of diverse microalgae species with sundry biochemical profiles, prospects for carbon dioxide sequestration, and either limited or near absolute monopoly from the perspective of food production modalities and logistics. However, attributing to a wide range of factors,

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for instance the insipid characteristic of microalgal cultures, and the fact that microalgae cells possess trivial sizes, the process of biomass production and subsequent conversion into biofuels become prohibitively expensive. As a consequence, from an economic outlook, the large-scale production of biofuels from microalgae achieves a somewhat less appealing status, compared to the other biomass types and sources. The current chapter delivers an outline of the bioeconomy analysis for microalgae-derived biofuels. In addition, case studies on microalgal biofuel production are presented along with cost estimations and the necessary strategies to augment its commercial viability.

Keywords Techno-economic assessment · Biofuel production · Microalgae-based biofuels

1 Introduction

Biofuels are widely perceived to be significantly prospective alternatives to the traditional and non-renewable fossil fuels, attributing to their characteristics such as sustainability, and the capabilities to reduce the emission of greenhouse gases, thereby achieving the ‘green’ status (Demirbas 2007). Recently, global biofuel production has witnessed a rapid growth, increasing from 19.651 million tons oil equivalent (toe) in 2005 to 74.847 million toe in 2015 (BP 2016). Biofuels can be derived from a wide array of biomass materials, including agricultural crops, municipal wastes, agricultural and forestry byproducts, and aquatic products. Out of all these sources, microalgae are commonly regarded to be the most suitable feedstock, owing to its high energy intensity, high average photosynthetic efficiency (50 times that of the terrestrial plants), and high capabilities of oil production (12,000 L biodiesel per hectare) (Gao et al. 2011). In addition to these characteristics, conceivable exploitation of barren lands and water bodies makes microalgae a perfect substitute for biomass which requires high agricultural input (Hill et al. 2006; Quinn and Davis 2015).

Driven by the aforementioned advantages, both industries and academia have initiated agendas to devote time and efforts for microalgal cultivation and biofuels production, thereby leading to their considerable and continuable development. The global production of *Spirulina* biomass had increased from almost nil to nearly 3500 tons (1000 tons = 1016 tons) from 1975 to 1999 (Pulz and Gross 2004). The microalgae industry had evolved with an annual production of 7000 tons of dry matter in 2004 (Brennan and Owende 2010). The majority of the companies (~78%) contributing to the algal biofuel growth are based in the USA, followed by Europe (~13%), and auxiliary states (~9%) (Bahadar and Khan 2013). To date, the US Department of Energy (DOE) has spent about USD 85 million to develop algal biofuels through some 30 R&D initiatives or so. In addition, for the purpose of manufacturing algal oil, Aurantia, a Spanish renewable energy company, and the

Green Fuel Tech of Massachusetts (USA), have commenced a USD 92 million project alliance in 2007. It is expected that in the conceivable future, this project targets an increase of nearly 100 ha of algae greenhouses, which will yield 25,000 t of algal biomass annually (Bahadar and Khan 2013).

Although the technical feasibility of microalgae has already been proven experimentally, the microalgae-based biofuels are yet not suitable for large-scale commercial applications, even after several decades of development. The major hindrance to this end is the relatively enhanced production cost. In order to realize a 10% return rate, investigations reveal that the essential selling costs of the product per gallon of triglyceride (TAG) should be USD 18.10 for PBR and USD 8.52 for open pond manufacturing. The biodiesel production costs per gallon of diesel via hydro-treating soared to USD 9.84 and USD 20.53, while the manufacturing price per gallon for petroleum diesel was USD 2.60, clearly indicating the increases expenses associated with the former (Davis et al. 2011). US DOE reported that algal biofuels can be competitive with petroleum at approximately USD 2.38/gal (DOE 2010). It is thus obvious, that in order to seek solutions for downregulating the increased production costs, the R&D sector is dedicated to carry out frequent and elaborate analyses of economic practicalities of microalgae-based biofuel.

Techno-economic assessment (TEA) is one of the most basic and common methods applied to evaluate the feasibility of microalgae-based biofuel. TEA methods are often associated with process modeling. In 2011, Ryan Davis modeled a microalgal setup producing raw oil in the annual capacity of 10 MM gal via the Aspen Plus software, to study the cost of each process unit of fuel production. The firm inferred that the microalgal biofuel production finances would be far from being reasonable with conventional fossil fuels, in case it corresponded to construct a large-scale manufacturing setup (Davis et al. 2011). Amer et al. (2011) have reported, by comparing five microalgae to biofuels processes using the SAFEER model, that the open pond scenarios which produced either TAG or free fatty acid methyl esters, appeared to be closest to the USD 1/kg price reference, and consequently, are the most viable choices (Amer et al. 2011). In another work, Zamalloa et al. (2011) considered the anaerobic digestion of microalgae and utilized a process model and diverse indicators to conduct the analysis of uncomplicated biomethanation potential. The results highlighted the efficacy of treating electrical and heat energies equally through a feed-in price of €0.133/kWh, making the project lucrative. This stands in poor contrast to the carbon credit of €30/ton CO_2(eq), with a meagre 4% revenue returns (Zamalloa et al. 2011). Batan et al. (2016) employed a dynamic accounting model of a bounded photobioreactor microalgal facility with a manufacturing capacity of 37.85 million liters (10 million gallons) of biofuel per annum. The authors showed that the total manufacturing costs of algal raw oil and diesel per liter matched to USD 3.46 and USD 3.69, correspondingly. The financial feasibility of biofuels manufactured from microalgae relies on the entree to coproduct arcades with more incremental benefits (Batan et al. 2016). The aforementioned studies ignored the impacts of either policies or byproducts. It may be noted that the absence of these two factors could influence the accuracy of the assessments to a certain extent. Additionally, the cost of land should also be taken into consideration.

Life cycle assessment (LCA) integrated with TEA modeling is a useful tool to assess the impact of the microalgal biofuel manufacturing process over the life-cycle. In 2016, a cohesive prototype for algal biofuel synthesis was reported by Dutta et al. (2016), which assists in running a life cycle valuation and a financial practicability scrutiny, aimed at the large-scale solicitation for economic implementation of the translation routes of microalgae-derived biofuel production. The authors investigated the sustainability of microalgae-derived biofuel production of transformation routes at University of Aveiro, Portugal, and at the National Renewable Energy Laboratory, Colorado, USA, and have reported that the capital value enhancement of coproducts is predominantly noteworthy because it augments revenue which may be utilized to advance the closing fuel vending cost (Dutta et al. 2016). López-González et al. (2015) adopted concurrent differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) coupled with mass spectrometry (MS), to simulate thermochemical performance and LCA to assess environmental viability and monetary sustainability of the pyrolysis and combustion of microalgae and their oils, establishing economic feasibility of the microalgal oil pyrolysis procedure at bulky manufacturing levels (López-González et al. 2015). In contrast to the previous studies, Malik et al. (2015) used a cross-regional and fiscal input–output prototype of Australia, supplemented with engineering course statistics on algal bio-crude manufacturing to assume crossbreed life cycle evaluation for determining the primary and secondary effects of bio-crude synthesis. The results demonstrate a net carbon-negative tendency of the algal bio-crude manufacturing method. Additionally, prospects of nearly 13,000 fresh jobs along with USD 4 billion value of incentives are synonymous with manufacturing 1 million tons of bio-crude, thereby providing a boost to the economy (Malik et al. 2015). The challenge of LCA methods is that the variances in scheme restrictions and the central LCA conventions will lead to dissimilar results. It is a fact that alterable suppositions related to the coproduct distribution approaches, sourcing of electrical energy, and life cycle catalogue information vividly influence outcomes. Hence, any additional alteration in administering trails and impractical authentication of sub-processing prototypes, with small-scale statistics, will provide higher erraticism in the reported outcomes (Quinn and Davis 2015).

Supplementary explorations have been directed utilizing process modeling as the core. Delrue et al. (2012) focused on establishing a model with four assessment norms: the net energy ratio (NER), manufacturing price of biodiesel, greenhouse gas (GHG) release proportion, and water footmark, to evaluate the economic, sustainable, and energetic performance of biodiesel and other biofuel productions from microalgae. They considered three processes: hydrothermal liquefaction (HTL), oil emission, and alkane discharge and showed that HTL may be contemplated either as a substitute to wet lipid isolation, and that lipid secretion is a better choice than the typical lipid extraction process. Delrue et al. (2012) have also compared a state-of-the-art trail (hybrid raceway/PBR cultivation scheme, belt filter press for dewatering, wet lipid isolation, oil water handling and oxygen deprived residual ingestion) with a reference pathway and found that the pioneering route optimized the energy and environmental measures with a relatively high production cost for economic viability (Delrue et al. 2012, 2013). This could be improved by integration with a long-term assessment. Furthermore, research using gauges such as return on investment (ROI) and net present value (NPV), will certainly foresee long-term profits of microalgae-based biofuel industry, with more systematic consequences.

The precise objectives of this chapter are to investigate the bioeconomy of large-scale microalgal biofuels production and to identify the key factors responsible for enhanced cost. To this end, the current chapter will provide valuable information for scaling and commercialization of microalgae-based biofuels.

2 Methods

2.1 Cost and Revenue

According to Xin et al. (2016), the cost of algae-derived biofuels can be divided into three categories: capital investment, total fixed operating cost (TFOC), and total variable operating cost (TVOC). Both capital investment and TFOC may be obtained directly through summation of their corresponding sub-items in dollars per year. The revenue may be obtained in the similar way. However, as the units of TVOC are usually MJ/d and kg/d, TVOC items are generally estimated based on the operation time. Therefore, an estimate of the total theoretical cost could be obtained from the sum total of capital investment, TFOC and TVOC. In case there are byproducts in the production process, the actual cost equals to the difference of theoretical cost and the economic value of the byproducts. Detailed information with respect to costs and revenue is presented in the supplementary information.

Two economic indicators, namely the NPV and the ROI, are usually adopted for the economic analysis. NPV is an indicator for analyzing the profitability of an investment or a project. Alternatively, it measures the profit by computing the costs and benefits for each period of an investment or a project. NPV may be estimated as:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{C_1 - C_0}{(1+r)^t} \tag{1}$$

where T is the time of cash flow, representing the time span during which the project is under operation and expected to have income; r stands for discount rate, i.e., the required rate of return that could be earned each period on a project with similar risk, which is set as 10% in this study; C_1 is the annual income (the benefits) and C_0 stands for annual expenditure. A positive NPV value indicates that the income brought by a project or investment has exceeded the anticipated costs, suggesting that the project or investment is acceptable, and vice versa.

ROI is used as a decision tool that allows the stakeholders to evaluate the performance of an investment or a project and compare it to others in their portfolio. The current study also uses this indicator to evaluate the efficiency of the algal biofuels production. ROI can be estimated as:

$$\mathrm{ROI} = \frac{\sum_{t=0}^{T} C_1 * P_t}{\sum_{t=0}^{T} C_0 * P_t} \tag{2}$$

where T represents the operation time, C_1 is the capital investment in dollars per year, C_0 stands for annual expenditure, and P_t is the discount factor in year t.

2.2 Sensitivity Analysis

The usual purpose of the sensitivity analysis is to investigate the potential changes in inputs and the corresponding effects on the economic output. Hence, the current work employs sensitivity analysis to identify the influence of each type of inputs on the basis of the economics, which may provide valued evidence for cost reduction. A typical sensitivity analysis comprises of five steps. The first step is to determine the indicators, such as payback period, ROI, NPV, and earnings before interest and tax. The second and third steps correspond to the estimation of the technical target values, and the selection of uncertainties, respectively. Particularly, in the third step, the factors that have higher probabilities of change and superior impacts on the target values of economic analysis are chosen. This is followed by the fourth step, where the influences of these uncertainties on the target value are quantified. Lastly, a comprehensive analysis is conducted and some insightful suggestions are proposed in the fifth and final step, based on the outcomes from the previous four steps.

2.3 Data Sources

Detailed data are elaborated in the supplementary information.

3 Results and Discussion

3.1 Algae-Derived Ethanol

3.1.1 Cost and Revenue

The total cost to manufacture one tonne of algae-derived ethanol is USD 6410. As depicted in Fig. 1, the highest cost is attributed to TFOC, occupying about half of

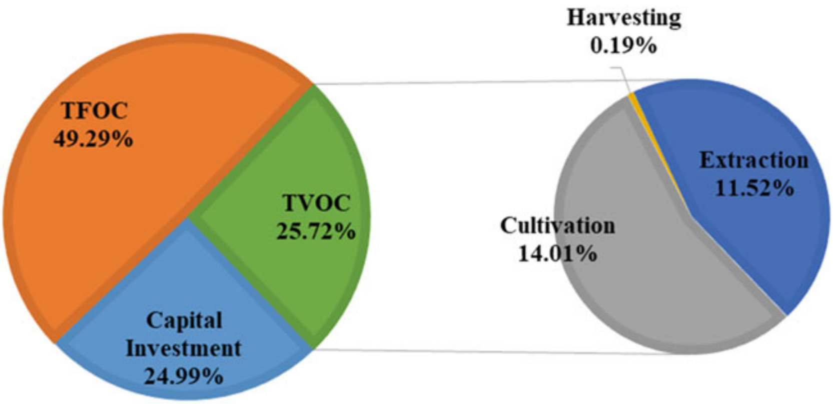

Fig. 1 Theoretical cost structure of algal ethanol

the total cost, followed by TVOC (25.72%) and TVOC (24.99%). Owing to a large number of inputs in the first year, the cost of the project amounts to be the highest during the operation period. Inevitably, this study chooses the first year to elucidate the structure of the cost (see Fig. 1). The capital investment in the first year has an economic value of USD 2.66 million, covering the costs of fixed assets involving equipment procurement and building constructions, such as photobioreactor (PBR), greenhouse, pyrolysis system, flocculation tank, centrifuge, land, storeroom. The investment for PBR is USD 1.28 million, which accounts for ~48% of the total cost. Meanwhile, the cost of the pyrolysis system and greenhouse constructions is among the principal sources of capital investments, responsible for ~17 and ~11% respectively, while the other costs possess comparatively subordinate contributions.

TFOC amounts to USD 1.56 million, with the major contributors as capital expenditures (~51%), depreciation (~17%), salaries (~14%), maintenance, insurance and taxes (~10%), among others. In a microalgal cultivation system, USD 26,763 and USD 161,457 are spent for the depreciation and maintenance of equipment annually to keep the system stable in the long run. Roughly, USD 220,000 per annum is used as the wages for the proprietors and the working personnel. The costs of cultivation, harvesting, and extraction constitute TVOC (see Fig. 1), which is USD 815,033. Cultivation, which requires a large amount of energy and nutrient input, invariably occupies the top position in TVOC. Extraction, which consumes considerable amounts of electricity and chemicals, is estimated to cost USD 365,090. Harvesting triggers the lowest cost with a fraction of 0.12%.

As a matter of fact, several factors, such as microalgal species, cultivation system, lipid content, grease content, and conversion technologies, may influence the cost estimation. Moreover, climate and season transitions (especially the changes in temperature and sunlight), having significant impacts on the mixing of nutrients and algal productivity, will also affect the total cost. In general, the cost of biofuels, such as algae-derived ethanol, is still higher than that of the fossil oils.

The revenue brought by algae-derived ethanol project is USD 8020/ton, which is higher than the cost. The revenue corresponding to the algae-derived biofuel may be credited to two segments: the products and the cost savings. The products are mainly ethanol, syngas, other liquids, and biomass, generating USD 370,615; 47,607; 1,073,089; and 1,628,041 per annum, respectively. As the wastewater-based microalgal biofuel production system recycles, nutrients like nitrogen and phosphorus may be recycled for microalgal growth to synthesize biofuels, which also gains USD 564,768 annually via the saving costs. Moreover, USD 46,883 may be earned as the carbon credit, because algae can absorb CO_2 during its growth period.

3.1.2 NPV and ROI

Assuming the discount rate to be 8%, the annual NPV is estimated to be USD 2.69 million, suggesting that the project is worth investing. The project ROI is 17.57%, which is higher than the discount rate, and implies that the algae-derived biofuel project possesses good economic benefits.

3.1.3 Sensitivity Analysis

The analysis has been performed via selection of PBR cost, salaries, operating period, chemical consumption, energy consumption, and biomass price as parameters, to evaluate their impressions on the economic cost, subject to an increase or decrease by 20% (Fig. 2).

The cost of algae-derived biofuel is most sensitive to the biomass price. The rising selling prices of biomass will greatly increase the profits of products and byproducts, ultimately lowering the actual economic cost. A 50.15% rise in the cost has been estimated, following a 20% increase in the biomass selling price. Thus, improving cultivation technology and promoting microalgae recovery efficiencies, oil extraction, and conversion rate, are a few effective approaches to enhance the economic performance.

In addition, the impacts of PBR cost, and operating period of the system on actual economic cost are significant. PBR is one of the principal project devices and incurs high expenses as well. It is anticipated that the breakthrough in the procurement of equipment, as a result of scientific and technological progress, will eventually reduce the cost of equipment input. Moreover, operation time constitutes a significant factor, having substantial connections with investments including the rental price of the land, energy, chemical and nutrient consumption, and wastewater cycling rate. A $\sim 14\%$ increase in the tangible cost is probable, provided the operation time is cut down by 20%.

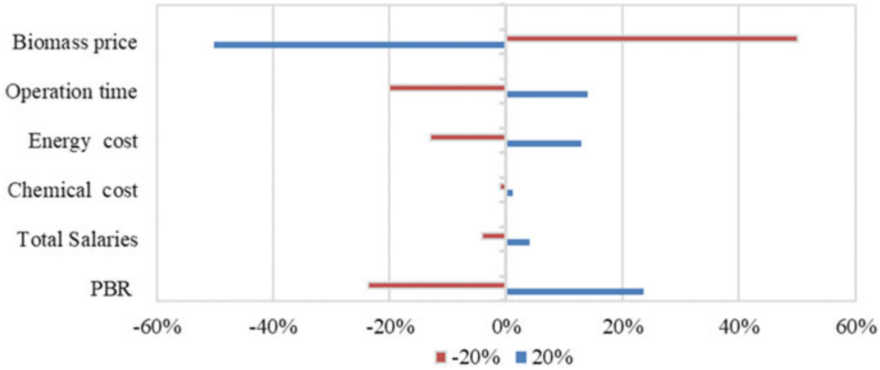

Fig. 2 Sensitivity analysis for the algal ethanol production system

Currently, the operation of the whole cultivation system is based on the electric system. As a result, the energy consumption is indispensable. Increase or decrease in energy consumption by 20% will lead to a 12.89% reduction or increase in ROI. Compared to the aforementioned factors, however, total salaries and chemical consumption do not strongly impact the cost. This is due to several reasons. Since the cultivation system is highly automated, only restricted labor is necessary for management and maintenance. It should be noted that nutrients like nitrogen and phosphorus are derived from the municipal wastewater. Consequently, a certain portion of the funds is protected as there is no need to buy extra nitrogen and phosphorus, which also hints at efficient regulation of chemical consumption.

3.2 *Algae-Derived Biodiesel*

3.2.1 Cost and Revenue

Mostly, the economic cost is a manifestation of an amalgamation of material inputs, labor, equipment repair and depreciation, and non-production inputs. It is assumed that the project will be operative for 200 days annually and will last for 15 years, according to Yang (2015). In summary, the first-year costs amount to USD 5246/ton, which is the largest among the operation period. This is because several items act as the first-year inputs. The average annual cost of the algae-derived biodiesel is USD 3523/ton. Taking the byproduct revenue into consideration, the cost will abruptly reduce to USD 960/ton.

In a similar fashion, the first-year structure is portrayed in Fig. 3. Material inputs, including energy, land, water, nutrient, catalyst, dominate the total production cost per ton of the algae-derived diesel. The cost of material inputs is up to USD 3415, corresponding to ~65% of the total cost. Among the material inputs, nutrients such as nitrogenous and phosphorus fertilizer yield the largest share,

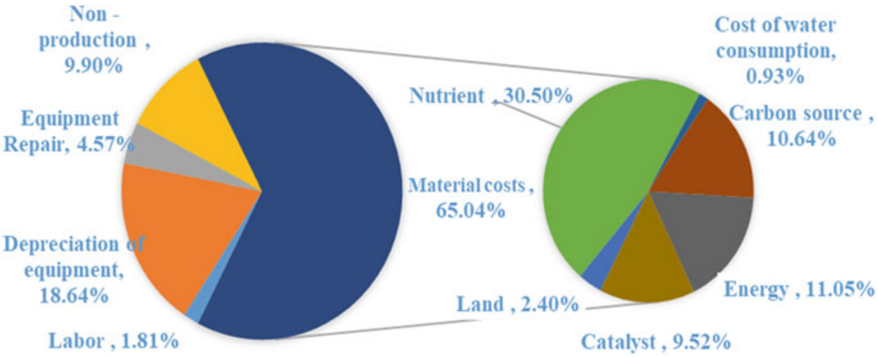

Fig. 3 Structure of algal biodiesel production costs

with >30% of the total cost. Energy consumption chiefly includes electricity, steam and transport fuel consumptions. Owing to extensive energy utilization in a variety of diverse processes, energy consumption takes the second position in material costs, with a value of USD 579.77 USD/ton (~11% of the total cost). Carbon dioxide, a necessity for algal growth, is the third largest source of material cost. To generate 1 ton of algae-derived biodiesel, USD 558.22 worth of carbon dioxide is required. In addition to the material inputs, algae-derived diesel production also demands equipment such as flocculation tank and centrifuge. Henceforth, the cost evaluation should take the equipment depreciation and repair into consideration. The results show the relative significance of these two cost sources, which contribute to nearly a quarter of the total cost.

Costs pertaining to the non-production inputs, i.e., administration, finance, and sale, are largely influenced by the management and the enterprise operation. The non-production cost is virtually unaffected and is directly correlated with the stability in the technology and management sectors. According to Yang (2015), the non-production costs account for approximately 9.9% of the total cost. Algae-derived biodiesel production mainly needs labor during the process of algae cultivation and biodiesel production. In this study, the monthly labor wage per person is assumed to be about USD 375. The total labor expenditure accounts to a small fraction (~1.18%) of the total cost.

The total annual revenue of the algae-derived biodiesel is USD 3676. The byproducts of biodiesel mainly include algal residue, pastry, glycerin, and methyl alcohol. Methyl alcohol may be used in the microalgae cultivation process to reduce the costs of chemical reagent consumption due to its relatively high price. The algal residue may be directly sold as animal feed (USD 640.03/ton) and fermentation feed (USD 447.47/ton). Meanwhile, post raw materials fermentation, the manufactured biogas (USD 212.11/ton) may be sold directly, or may be used as the feed gas for boiler gas production (USD 209.86/ton), power generation (USD 115.20/ton), and purification (USD 220.66/ton). Consequentially, to advance the economic benefits of the algae-derived biodiesel system, it is advised to vend the algal residue, yielded from microalgae biodiesel production, directly. Moreover, the algal residue may generate biogas via anaerobic fermentation. Biogas may be isolated to refined gas and CO_2. While the refined gas may be utilized as the conventional energy source for daily household use, CO_2 may be recycled for algal cultivation, which proves to be beneficial and cost effective.

3.2.2 NPV and ROI

Based on the cost and benefit data, ROI of microalgae diesel is 7.78% and the net present value (NPV) is USD 640.

3.2.3 Sensitivity Analysis

For the sensitivity analysis, an ensemble of parameters are selected: microalgae biomass per unit area, oil content, annual run time, recovery rate, oil extraction rate, CO_2 absorption rate, nutrient consumption, chemical reagent consumption, and wastewater recycling rate. The variations in microalgae diesel investment rate of return (ROI) are estimated following a ±20% alteration in any single parameter, as shown in Fig. 4.

Figure 4 indicates that the total price of the algae-derived biodiesel is maximally perceptive to nutrient utilization. There is a fluctuation in the total cost from −7.56 to 10.87%, following a ±20% alteration in the lipid content. In addition, any change in nutrient consumption strongly influences the cost. For instance, following a ±20% change in the nutrient assimilation, the total cost change varies by a margin of ±6%. Furthermore, following a ±20% change in either the recovery or the oil extraction efficiency, the total cost change will vary between −4.4 and 6%.

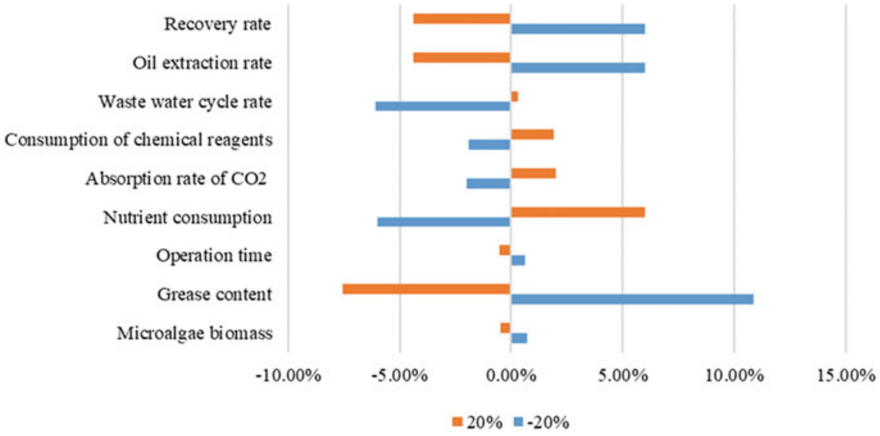

Fig. 4 Sensitivity analysis for algal biodiesel system

Thus, improving recovery and oil extraction efficiencies will definitely impact the total cost in a positive manner.

Based on the sensitivity analysis, it may be inferred that the most effective method to decrease the total price of the algae-derived biodiesel is to increase the microbial biomass and the grease content. Efforts should be made during microalgal cultivation, processing, and transformation. For instance, genetic engineering can be employed to enhance the grease content, and the algal growth rate. Other measures such as refining the carbon absorption rate and discovery of cost-effective carbon and nutrient sources are also effective ways to reduce the production cost of the microalgal biodiesel. Additionally, the choice of appropriate climate for microalgal culture, mounting the microalgal breeding time, enhancing microalgal recovery, oil extraction, and oil conversion efficiency, is all beneficial for down-regulating the cost of biodiesel production. However, efforts pertaining to the reduction of fixed investment, chemical reagent consumption, and energy consumption may lead to the cost reduction only to a certain extent, with limited effects.

4 Conclusions

The current study conducted an all-inclusive bioeconomy analysis for the algae-derived biofuel projects, such as the bioethanol and biodiesel projects. Based on the available applied data, the cost and revenue for the former is USD 6410 and USD 8020/ton, while that of the latter is USD 3523 and USD 3676/ton. Compared to the fossil fuels, the economic outputs of algae-derived biofuels are a few notches higher. NPV possesses a positive value, indicating that both the projects are worthy of probable ventures. The outcomes of sensitivity analysis imply that efficient measures such as reducing energy consumption, and increasing the microbial biomass, and grease content, are conceivable elucidations to achieve a more economically feasible status for the algae-derived biofuel.

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References

Amer, L., Adhikari, B., & Pellegrino, J. (2011). Technoeconomic analysis of five microalgae-to-biofuels processes of varying complexity. *Bioresource Technology, 102*(20), 9350–9359.

Bahadar, A., & Khan, M. B. (2013). Progress in energy from microalgae: A review. *Renewable and Sustainable Energy Reviews, 27,* 128–148.

Batan, L. Y., Graff, G. D., & Bradley, T. H. (2016). Techno-economic and Monte Carlo probabilistic analysis of microalgae biofuel production system. *Bioresource Technology, 219,* 45–52.

BP. (2016). S*tatistical Review of World Energy June 2016*. BP global.

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews, 14*(2), 557–577.

Davis, R., Aden, A., & Pienkos, P. T. (2011). Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy, 88*(10), 3524–3531.

Delrue, F., Li-Beisson, Y., Setier, P. A., Sahut, C., Roubaud, A., Froment, A. K., et al. (2013). Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria. *Bioresource Technology, 136,* 205–212.

Delrue, F., Setier, P. A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., et al. (2012). An economic, sustainability, and energetic model of biodiesel production from microalgae. *Bioresource Technology, 111,* 191–200.

Demirbas, A. (2007). Progress and recent trends in biofuels. *Progress in Energy and Combustion Science, 33*(1), 1–18.

Dutta, S., Neto, F., & Coelho, M. C. (2016). Microalgae biofuels: A comparative study on techno-economic analysis & life-cycle assessment. *Algal Research Biomass Biofuels and Bioproducts, 20,* 44–52.

Gao, C. F., Yu, S. S., & Wu, Q. Y. (2011). Progress in microalgae based biodiesel. *Bulletin of Biology, 46*(6) (in Chinese).

Hill, J., Nelson, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America, 103*(30), 11206–11210.

Lopez-Gonzalez, D., Puig-Gamero, M., Acién, F. G., García-Cuadra, F., Valverde, J. L., & Sanchez-Silva, L. (2015). Energetic, economic and environmental assessment of the pyrolysis and combustion of microalgae and their oils. *Renewable and Sustainable Energy Reviews, 51,* 1752–1770.

Malik, A., Lenzen, M., Ralph, P. J., & Tamburic, B. (2015). Hybrid life-cycle assessment of algal biofuel production. *Bioresource Technology, 184,* 436–443.

Pulz, O., & Gross, W. (2004). Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology, 65*(6), 635–648.

Quinn, J. C., & Davis, R. (2015). The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. *Bioresource Technology, 184,* 444–452.

U.S.DOE. (2010). *National algal biofuels technology roadmap*.

Xin, C., Addy, M. M., Zhao, J., Cheng, Y., Cheng, S., Mu, D., et al. (2016). Comprehensive techno-economic analysis of wastewater-based algal biofuel production: A case study. *Bioresource Technology, 211,* 584–593.

Yang, Y. (2015). Economic cost analysis of biodiesel from microalgae cultivated in open pond. *Acta Energiae Solaris Sinica, 36*(2), 295–304. (in Chinese).

Zamalloa, C., Vulsteke, E., Albrecht, J., & Verstraete, W. (2011). The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology, 102*(2), 1149–1158.