Techno-Economics and Sensitivity Analysis of Microalgae as Commercial Feedstock for Bioethanol Production

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Abstract

The foremost purpose of this techno-economic analysis (TEA) modelling was to predict a harmonized figure of comprehensive cost analysis for commercial bioethanol generation from microalgae species in Brunei Darussalam based on the conventional market scenario. This model was simulated to set out the economic feasibility and probabilistic assumption for large scale implementations of a tropical microalgae species, *Chlorella vulgaris* for a bioethanol plant located in the coastal area of Brunei Darussalam. Two types of cultivation system: closed system (photobioreactor) and open pond approach were anticipated for total approximate biomass 220 tonnes y^{-1}on 6 hectare coastal areas. The biomass productivity was 56tonnes hectare^{-1} for photobioreactor and 28tonnes hectare^{-1} for pond annually. Plant output was 58.90m^3 hectare^{-1} for photobioreactor and 24.9m^3 hectare^{-1} for pond annually. Total bioethanol output of the plant was 57,087.58gallony^{-1} along with value added by-products (crude bio-liquid and slurry cake). Total production cost of this project was 2.22 million US$ for bioethanol from microalgae and total bioethanol selling price was 2.87 million US$ along with by-product sale price 1.6 million US$. A sensitivity analysis was conducted to forecast the uncertainty of this conclusive modelling. Different data sets through sensitivity analysis also presented positive impact for economical and environmental view. This TEA model is expected to be initialized to determine an alternative energy as well and minimize environmental pollution. With this current modelling, microalgal-bioethanol utilization mandated with gasoline as well as microalgae cultivation, biofuel production integrated with existing complementary industries are strongly recommended for future applications.

Keywords: Bioethanol; Life Cycle Cost; Microalgae; Payback Period; Sensitivity Analysis; Techno-Economic Assessment

Nomenclatures

Symbol	Description	Unit
DE	Delivered Equipment	$
FCI	Fixed capital investment	$
i	Project year	year (y)
LCC	Life Cycle Cost	$
MC	Maintenance Cost	$
n	Project life time	year (y)
OC	Operating Cost	$
OLC	Operating Labour Costs	$
PP	Payback Period	Year (y)
RMC	Raw Material Cost	$
SV	Salvage Value	$
TAX	Total Tax	$
TBS	Total Bioethanol Sale	$
TBPS	Total By-Product Sale	$
TCAC	Total Cultivation Area Cost	$
TCI	Total Capital Investment	$
TEC	Total Equipment Cost	$
TPC	Total Production Cost	$
TPP	Total Plant Profit	$
TUC	Total Utility Cost	$
WC	Working Capital	$

Introduction

In the recent world, energy turned into a key driving force to be researched for enhancing the optimized usages and generating renewable sources due to tremendous depletion of fossil fuel and threatening greenhouse effect[1, 2]. In this regard, alternative source of energy generation became a crucial concept to be considered. Renewable energy production such as biofuel is the best choice to be applied for generating alternative energy source[3]. Among various biofuels, bioethanol has been considere das one of the leading and popular source of bio-energy, especially for transportation fuel blended with gasoline and diesel now-a-days[4-7]. Bioethanol contains very high relative octane number (RON), self-ignition capability by low cetane number (LCN), notable heating value for evaporation and low carbon mono-oxide (CO) emissions to the environment[8]. Several countries worldwide already initiated producing bioethanol for fuel purpose since 1980s' such as United States, Brazil, China, Canada, India and others and production in the US was the most. **Fig.1** and **Fig.2** showed the latest scenario of bioethanol production worldwide and the bioethanol production rise curve in the US, respectively[9].

Fig. 1. Worldwide Bioethanol Production in 2015 [9]

Fig. 2. Bioethanol Production Rise Curve in U.S. (2000-2015) [10]

Currently, many feedstocks are being experimented and utilized for bioethanol mercantile production. First generation biofuels (extracted from palm oil, soybean oil, sugarcane and others) caused escalation of food prices and diminished food sources for human and animals. Second generation biofuels (extracted from non-food biomass e.g. sugarcane bagasse, agricultural residue, grass and others) are not feasible due to the high cost of pre-treatment[11]. To resolve this issue, bioenergy experts were searching for3rdgenerationbioethanol sources and identified microalgae for bioethanol production since several types of them are enriched with carbohydrate to generate an immense amount of bioethanol than other energy crops. The bioethanol yield comparison among various energy crops and microalgae was presented in **Fig.3**. Besides bioethanol production, microalgae used to treat wastewater by using CO_2 and waste components as nutrients and released O_2 (Rc. 1) to the environment that turns down environmental pollution[11-13]. Apart from this, the amount of CO_2 produced during fermentation of algal sugars to bioethanol, can be fed to the microalgae culture as a microalgal growth component[14].

$$6CO_2 + 12H_2O + Light \rightarrow C_6H_{12}O_6(Carbohydrate) + 6O_2 + 6H_2 \qquad (1)$$

Techno-economic analysis (TEA) is one of the most significant issues for any industrial application of research output as economic feasibility is the major concern of commercial execution of any product[15]. This study constructed a TEA modelling of bioethanol production from microalgae by reviewing energy and cost scenario of similar types of bioethanol project worldwide. This modelling has been emerged to strike highly on the current biofuel scenario in South-East Asia. The application of microalgae biomass on bioethanol in industrial level has not been practiced much in South-East Asia, especially not in Brunei Darussalam. In this region, the climate is exquisitely suitable for microalgae cultivation[16, 17].

The TEA modelling was projected for Brunei Darussalam on the island of Borneo in Southeast Asia. Brunei Darussalam was in outlook for the bioethanol plant modelling from microalgae for several aspects such as tropical climate. That is perfectly favourable for high rate of microalgae growth. The country also have coastal territory which is commendatory for marine algae cultivation, plenty of barren inexpensive coastal area to establish bioethanol plant with minimum cost, handiness of marine water, direct sunlight through the year and cheaper labour cost[18-21]. A survey in Brunei reefs clarified that Brunei currently is experiencing high rates of microalgae growth in coastal area as well as escalating CO_2 emission in environment by highly fossil fuel usages[22-24]. Consequently, microalgae cultivation for green energy (bioethanol) production at industrial level is highly expected to mitigate free CO_2 in the air and utilize the suitability of the microalgae growth environment. The specific predominant tropical species of microalgae *Chlorella vulgaris* was preferred for this TEA due to the availability of this species in the selected region and high content of carbohydrate amount[25, 26]. The overall economic conditions and costs associated with microalgae cultivation to the bioethanol production and purification were illustrated exhaustively in this study. This TEA model also illustrated economic practicability for large extent. **Fig.4** showed the technical treads to generate bioethanol from microalgae chronologically and economical assessment based on these technical procedures[27].

Fig. 3. Bioethanol yield comparison among various sources[28]

Fig. 4. Technical steps for bioethanol production from microalgae[29]

This TEA modelling emphasized on environmental and economical prospects. To illustrate the environmental factor, microalgae is cultivated for wastewater treatment in many industries since it is capable to utilize waste components, inhale CO_2 as food sources for growth and exhale O_2 to the environment[30]. Thus, no carbon payback period is required and that is the most significant knock for cleaner and greener environment. The economic factor is coupled with the superficial richness of carbohydrate content to produce plenty of bioethanol from it. Several species and strains of microalgae are capable to produce high amount of carbohydrates which is the main driving factor for bioethanol production. For instance, *Chlorella vulgaris* is one of these microalgae species[12, 28, 31, 32].

The main objective of this research was to cultivate microalgae efficiently through both techniques that are pond and photobioreactors. The commercial microalgae cultivation system is far different than other usual energy crops. The techniques involved are quite new in most of regions in the world and the industries might endure some risk factors due to this point[33]. The aim of this study is to draw a detailed design of techno-economic assessment of a scale-up bioethanol generation plant from microalgae in a Brunei costal area. That accounted every single cost of fixed and variable components for a whole project lifetime through 20 year period. The analysis includes the sensitivity analysis; determine the life cycle cost assessment, cash-flow, break-even analysis as well as payback period to retrieve the total capital investment. The start-up period and total plant profit amount were determined to illustrate whether the project is desirable economically for future establishment or not[34].

To establish a detailed techno-economic assessment model was very crucial due to several rationales[35]:

i. Techno-economic analysis is the initial phase to transform lab scale invention to industrial application.
ii. To verify the bioethanol output from microalgal biomass through commercial scale is economically viable and realistic or not.
iii. To estimate the total plant profit as the key point to attract industrial market.
iv. To develop a mixed process combined with traditional (ponds) and advanced technological (photobioreactors) approaches as a form of the optimization process of bioethanol plant design from microalgae.
v. To inspect an ideal bioethanol generation plant from microalgae where every step (from microalgal cultivation to bioethanol purification) of biomass production to pure product manufacturing is included to integrate with by-product generation.

Materials and Methods

Materials

In this study, *Chlorella vulgaris* was utilized for bioethanol production due to the high cellulosic carbohydrate content as well as availability and growth capability in this tropical region. *Chlorella vulgaris* is spherical shaped, single cells (with nucleus) microalgae, contains cellulose and hemicelluloses (carbohydrate components) in cell wall and starch is the main carbohydrate storage product[12]. *Chlorella vulgaris* dry biomass contains 52% carbohydrate during hydrolysis period producing glucose yield 90.4% by the fermentation process and produced almost 88% bioethanol yield[28]. A comparison table of *Chlorella vulgaris* with other tropical microalgae in terms of carbohydrate content has been tabulated in **Table 1**.

Table 1

Comparison between studies species and other microalgae species in the projected location in terms of carbohydrate accumulation [28, 36]

Thus, the finding stipulated the economic feasibility and efficiency of microalgae for bioethanol generation in commercial level[31]. Among various microalgae species and strains, *C. vulgaris* was manifested the best fitting to produce carbohydrate. It is easy to sequence the genome and recombination for the yield improvement of this species in future. Hence, this type of microalgae species was considered to cultivate for a TEA model[37].

Methods

Data Collection

Process design and data collection is one of the most crucial factors for TEA. In this project, the process design, planning and input data were assembled from diverse types of sources. The sources were bioethanol production experts, bioethanol production companies' database and reports, researcher-experts in bioethanol and microalgae fields, related journal articles, technical datasheets, suppliers and manufacturers, up-to-date websites for market price for items included in the project.

Techno-economic model of large-scale bioethanol production plant from microalgae was simulated with integrated process design. The simulation model was plotted based on the universal economic analysis of several chronological phases such as microalgae cultivation, biomass pre-treatment, extraction and fermentation, bioethanol separation and purification diagrammed by **Fig.5**[38-40].

Fig. 5. Technical process flow diagram of input, output and internal flows of the project

The operations and technologies in current process modelling was adopted by microalgae biomass cultivation in Tuscany, Italy and bioethanol production in Italy[38, 41]. The coastal area of Brunei Darussalam was preferred as plant location since the cultivation water will be submerged from sea, suitable climatic condition and cheaper land and these conditions carried similarity with model plant type. The comprehensive process flow system incorporated few varied sectors such as 1. Microalgae cultivation in different approaches: pond system and photobioreactor, 2. Biomass pre-treatment, 3. Biomass extraction by extractor and fermentation by fermenter, 4. Bioethanol separation through the beer column and 5. Bioethanol purification through the rectifier. Several specific modifications for this modelling were mentioned here[38, 41].

1. Two submersible pumps were planned to be used, one pump was for seawater withdrawal and another for water supply to ponds and PBR.

2. The single circulation pump will be used for each reactor and pond and feed pumps for feeding nutrients to the cultivation systems. Heat exchangers will be used for cooling water and re-using it in order to save energy.
3. For piping and instrumentation design, PVC material will be used. Higher quality materials will be applied for photobioreactors for long lasting life-span. Sensors for pH, temperature, nutrient addition and contamination identifier will be used in order to control the microalgae growth rate.

However, all types of cost ventures, including direct cost (e.g. equipment cost), indirect cost (e.g. engineering and supervision cost, contingency, legal expenses and others), operation cost, raw material cost, utility cost, maintenance cost and others, total sale of produced bioethanol and by-products from the plants were carefully counted. Life cycle cost (LCC), total production cost (TPC), payback period (PP), total plant profit (TPP) were calculated. Cash flow diagram and break-even analysis were simulated based on the plant ventures and earnings using certain economical formulae[42]. The conclusive simulation and graphical presentations were constructed by using Microsoft Excel Software.

Techno-economic Simulations

Life Cycle Cost (LCC)

Life cycle cost (LCC) illustrated the costing calculation process of a plant, project equipments that include all the detailed cost information of the project lifetime. That includes all fixed capital cost and variable costs for manufacturing desired product[43]. In this TEA, LCC included total capital investment (TCI) and total production cost (TPC) where salvage value (SV) and total by-product sale (TBPS) were deducted. Salvage value (SV) defined the re-selling price of plant equipment after the usual project lifespan[40]. This project lifetime was drafted for 20 years and LLC was determined for the whole 20 years using the Eq.1 and Eq.2. LLC was plumbed based on the initial cost info and calculation for future projection. It may vary in real life in term of dynamic market of the costing[44].

$$LCC = TCI + TPC - SV - TBPS \quad (1)$$

$$LCC = TCI + \sum_{i=1}^{n} TPC_i - \sum_{i=1}^{n} SV_i + \sum_{i=1}^{n} TBPS_i \quad (2)$$

For total capital investment (*TCI*), salvage value (*SV*) and tax, the simulation formula is at Eq.3, Eq.4 and Eq.5, respectively:

$$TCI = FCI + WC + TCAC \quad (3)$$

$$SV = 0.05\ of\ FCI \quad (4)$$

$$Tax = 0.02\ of\ FCI \quad (5)$$

Total Production Cost (TPC)

Total production cost (TPC) was predictedon the basis of simultaneous costing analysis to producethe desired product, bioethanol. TPC for this project covered the sum of operation cost (OC), maintenance cost (MC) and raw material cost for 20 years of project lifetime (Eq.6). OC determined the total addition operating labor cost (OLC) and total utility cost (TUC) by (Eq.7)[45]. TPC assessed a fluid assumption for the project what may remain approximate simulated calculation or may change anytime based on the material and labor market demand and price[46].

$$TPC = \sum_{i=1}^{n}(OC_i + MC_i + RMC_i) \quad (6)$$

$$OC = \sum_{i=1}^{n}(OLC_i + TUC_i) \quad (7)$$

Payback Period(PP)

Payback period (*PP*) elucidated the estimation of projected years that is usually needed to recover the total cost total capital investment. Therefore, the profit of the plant was contingent on the years after the payback period. In this modelling, the PP was calculated as the ratio of TCI over yearly earnings from the bioethanol plant (Eq.8). Yearly earnings were the income from the total bioethanol sale and total by-product sales (crude bio-liquid and slurry cake) per annum where yearly production cost and tax were eliminated. PP also strongly depended on the variability of TPC in term of market fluidity. Tax is usually measured on an area basis since it varies from region to region [40].

$$PP = \frac{TCI}{TBS - TPC - TAX} \quad (8)$$

Total Plant Profit (TPP)

Total plant profit delineates the net project income from the plant within whole plant life. For this TEA, TPP was clarified by the total bioethanol sale (TBS) throughout the whole plant lifetime (20 years) where LCC was subtracted from it (Eq.9). TPP is considered as one of the first-rate strands to design a profit-oriented ideal plant. Usually the expected profit amount for a project relies on TPP simulations[47].

$$TPP = TBS_n - LCC \quad (9)$$

Cash flow and Break-even analysis

To deal with the series of cash flow of 20 years for the project, cash amount was calculated for each year. Cash flow for this TEA was conducted for the profit facet and cash flow diagram rendered a brief view of cash incoming. Aside of that, cash flow also measures how favourable it would be for the project effectively. Cash flow of this project was calculated according to Eq.10[48].

$$Cash\ simulation(per\ year) = Cash\ Earning - Cash\ Investment \quad (10)$$

Break-even point defined the point where a total sale (*TBS* and *TBPS*) amount and the total invested amount of fixed and variable cost are uniform. Amounts before and after meeting break-even point have interpreted the loss and profit for the project, respectively. Break-even analysis amounts were calculated based on Eq.11 for each year.

$$Break - even\ point = (TBS + TBPS) - (TCI + TPC) \quad (11)$$

Cash flow diagrams and break-even analysis were simulated based on yearly cost investment and sales[48].

Sensitivity Analysis

Sensitivity analysis is an appraisal to analyze the uncertainty of the process with different scenarios in term of few major factors of the whole process from microalgae cultivation to bioethanol production from it[49]. Sensitivity analysis was performed for this project to investigate the projected alternations based on major factors regarding cost involvement of the plant set up and system-run. Bioethanol production cost from microalgae was the prime key vehicle for this techno-economic analysis study. Sensitivity analysis was conducted based on TPC for both PBR and pond cultivation methods of microalgae where chemical agents, nutrients, water, CO_2 prices were variedin different ranges. Furthermore, another sensitivity analysis was run for the alternative variations of combined TPC, Tax, SV, TBS, TBPS that influenced LLC and TPP[40, 49].

Results and Discussion

Techno-Economics Analysis

Most of TEAs and plant design are carried out to impart data collection and simulations regarding estimation of capital and operating costs. TEA estimation is a specific sector of engineering economics and management where usually engineers plan and simulate an approximate economic projection with the proper technological applications and optimized designs. This chapter introduced of capital and operating costs and the techniques used for estimation. The main methods used for economic evaluation of projects are introduced, together with an overview of factors that influence project selection[16, 50]. In addition, the process economics restrains three different fundamental attributions in system design that are design alternatives, optimizing the project in term of economic feasibility and overall plant benefit. For this project, two types of cultivation process were applied: PBRs and ponds and the desired dry biomass production amount were110 tonnes y^{-1} (100,000 kg y^{-1}) for each cultivation system and total bioethanol production annually was esteemed 220 tonnes y^{-1}[51]. Key assumptions for annual biomass production, required cultivation area, system geometry, bioethanol yield and production were presented in **Table 2** [41, 51].

Table 2

Key Estimations for Microalgae Cultivation and Bioethanol Production [41, 51]

Microalgae biomass productivity was 56 tonnes $ha^{-1}y^{-1}$ in PBR while ponds yielded 28 tonnes $ha^{-1}y^{-1}$ as PBR is closed system with very low possibility of contamination and controlled factors albeit pond cultivation is a cheaper and more land-consuming than PBR. Total productivity of both ways was lessened due to stress condition of carbohydrate content. Ponds occupied almost 4 hectares land to plough microalgae where PBR required only 2 hectares. Moreover, bioethanolic yield for PBR and the pond was 58.90m^3 $ha^{-1}y^{-1}$ and 24.94m^3 $ha^{-1}y^{-1}$, respectively. Although both of species contains more than 50wt% carbohydrates, in most cases of reality, it is usually expected 30%-40% (w/w). At the end, the total bioethanol output was 57087.58gallons y^{-1} from the projected plant (**Table 2**).

The total equipment cost (TEC) was designed to construct the plant and conduct the process. This cost comprised of the components: construction of ponds and PBRs, cost of water mixers, dose pump (supplementation, CO_2 supply), sensors (to control pH, water level, temperature, light amount), extractor (to extract biomass after pre-treatment), hydrolysis tank, fermenters (to hydrolysis and ferment the extracted biomass), scrubber, beer column (to separate bioethanol from crude bio-liquid and slurry cake), rectifier (to produce and purify bioethanol), evaporator and others. The construction cost of single PBR is more than 5 times higher than the traditional pond system due to technological advancement and high quality construction material (**Table 3**). The total cost of equipment was presented in **Table 3**[51] and **Fig.6** clarified the distribution of total equipment cost.

Table 3

Total Equipment Cost (TEC) [51]

Fig. 6. Distribution of Total Equipment Cost (TEC) estimation (%)

According to **Fig.6**, the dominant equipment expenditure was for PBR construction, beer column and others; for ponds construction and pumps purchase price was average and reasonable. The lowest budget in total equipment cost was for mixers and sensors. Total capital investment (TCI) was calculated to accumulate of newly produced physical entities, such as plant set up area, machinery, equipment, goods and inventories (**Table 4**). Fixed capital investment (FCI) demonstrated fundamental amount invested for installed equipment for the technical steps to operate the whole process. FCI incorporated direct costs (e.g. equipment delivery, installation, instrumentation controls, piping, electrical system, building, yard improvement, service facilities) and indirect costs (e.g. engineering and supervision, construction expenditure, legal expenditure, contractor's fees, contingency)[52]. Total cultivation area cost (TCAC) and working capital (WC) were covered under TCI (**Table 4**)[46]. **Fig. 7** showed the distribution of TCI. For this project, delivered equipment method was applied to estimate the capital investment. The fraction of delivering equipment method applied for this project was a fluid processing plant.

Table 4

Total Capital Investment (TCI) Calculation [46]

Fig. 7. Distribution of Total Capital Investment (TCI)

In this project, bioethanol was the main product, crude bio-liquid and slurry cake were the by-products. Both of by-products would be sold to other companies and retailers in the market. Crude bio-liquid maintains high market price due to medicinal, nutritional and other biofuel production values. Slurry cake usually is pressed into organic fertilizer. Total utility cost (TUC) was the expenses for electricity to run the plant process and produce UV lights for PBRs supply, gas and other heating fuels[46]. In this project, electricity was the dominating parameter for utility cost calculation. Operation cost (OC) was the sum up of operating labour cost (OLC) and TUC (**Table 5**). Operators were assumed to work on two shifts with $7h^{-1}$US$ every day of the year based on the local labour market in Brunei. The project was expected to run continuously and should be supervised daily basis (**Table 5**). Maintenance cost (MC) was the expenses for the equipment and plant maintenance on a yearly basis. It was counted based on a small fraction of TCI amount presented in **Table 5**)[35, 53-55]. The raw materials included water, nutrients, CO_2 and all chemicals for pre-treatment process (**Table 6**) of microalgae biomass.

Table 5

Cost calculation of OLC, TUC, OC and MC [35, 53-55]

Table 6

Raw Material Cost (RMC) [35]

Total production cost (TPC) combined of all the expenditure on operation cost, maintenance cost and raw material cost. This was considered one of the most crucial parts of the cost measurement for operating the plant and selling price for bioethanol and by-products[52]. **Fig.8** presented the distribution of bioethanol production cost for this project. The market price of the product (bioethanol) and by-products were demonstrated in **Table 7**[56, 57]. In this study, TPC was US$ 111066 y^{-1} to produce 200000 kg dry biomass annually where OC carried the most expenses US$89800 y^{-1}, RMC was US$13000 y^{-1} and the least expenses was on MC, US$8265.74 y^{-1} (**Table 8**).

Fig. 8. Distribution of bioethanol production cost from microalgae

Table 7

The market price of product and by-products [56, 57]

Since the design was upgraded, more information was gathered. The most favourable approach to analyse the profitability of the plant are based on life cycle cost (LCC) and total plant profit (TPP) estimation during this project life. The projected LCC and TPP for this study throughout its lifespan, usually form the basis for more elaborate estimation and prediction for establishment[34]. For this study, project lifetime was presumed as 20 years. It was expected that the whole project would perform efficiently with whole lifespan. Another prediction was that the whole project would be built up on individual funding and no loan was expected. LCC and TPP were set up based on these assumptions. The all production cost, tax, salvage value (SV), total product sale, LCC, TPP were presented in **Table 8** on annual and project lifetime basis[58].

Table 8

Key Simulations of Project Techno-Economical Assessment[58]

In **Table 8**, LLC for the 20 year project lifetime was US$2,274,463 where the total bioethanol sale, by-products sale and salvage value of the plant equipment were

US$286, 5797, US$1,600,000 and US$65,186.2 per project lifespan, respectively. **Fig.9** displayed the comparison between TPC and TBS. For most of plants, usually SV is estimated as zero, but for this project, it was predicted 5% of FCI (Eq.4) since photobioreactors are high-tech equipments and they last long period of time with efficiency[13]. TPP for this project was calculated as LCC was deducted from total sales of the products for 20 years and the TPP resulted well amount for the whole project lifetime US$591,333 with positive impact on existing environment. That also stipulated the project design and calculation assumptions profitable economically and environmentally with innovative findings.

Fig. 9. Bioethanol production cost vs. selling price

Payback period (PP) clarified the gross period, which elapses from the initiation of the project to the break-even point. The shorter the payback period is, the more attractive the project will be commercially[52]. Mostly PP is counted as the time to regain the TCI in terms of total annual sale (product and by-product sale), total production cost and tax[59]. In this study, payback time was calculated as the time to recoup the retrofit TCI from the annual improvement in operating costs[60] and it was only 0.74 years(**Table 8**).

Cash flow for this project was taken into account for every year from plant set up to end drawn by **Fig.10**. In the first year, for TCI, cash flow was down and then from next year, earning amount from TBS and TBPS started to add up and cash flow went up. The cash flow was constant after year 1 till before the year 20 since this TEA model expected similar profit in each year. The profits might vary after execution due to the market price variation in term of bioethanol production and selling cost, growth productivity of different microalgae batches and any other reasons. However, for the year 20, the earning amount was higher than previous years since SV was counted for the last year of the project. **Fig.10** presented the 20 years cash incoming and outgoing flow for the whole project.

Fig.10. Yearly based process cash flow diagram in terms of total investment and income

Fig.11 demonstrated the break-even analysis for this techno-economic project. In **Fig.11**, the graph denoted that the break-even point was at the year 11 what meant project needed 11 years to recover the TCI and TPC and after 11 years.The project started to get net profit until the last year.

Fig.11. Break-even analysis of the bioethanol production process from microalgae

Furthermore, for this project, the inflation rate was assumed unchanged or changed co-currently with input and output ratio. Generally, inflation causes the rise in the price of raw material, services, products and co-products over time. Inflation draws impact on the amount of money needed for purchasing raw material and services. Inflation was estimated by the percentage of the fractional manipulation in the cost with time-frame and calculated as a certain added percentage per annum, what impacts on annual price rates. The effect of inflation rate for this TEA can best be explained through examining such effects before and after project time zero[61].

Sensitivity Analyses

The sensitivity analysis was conducted for TPC to generate bioethanol from microalgae per annum for both photobioreactors are given in **Fig.12** and pond cultivation method is given in **Fig.13**. For PBR method, four specific raw material factors e.g. chemical agents, nutrients, water and CO_2 had liquidity based on different ranges of RMC on current market where chemical agent price influenced the most and nutrients and CO_2 did the least. Chemical agents' price can be varied from US$5,500 kg^{-1} annually to US$10,500$kg^{-1}$ annually (**Fig.12**). As the plant was planned to set up nearby coastal area, water source was freely accessible. Consequently, no extra cost was required for water source[32]. Nutrient and CO_2 costs were totally varied by the market based on availability and demand[62]. For the case of pond plough approach, only nutrients and chemical agent costs mattered and the cost variations were totally current market and demand based (**Fig.13**).

Fig.12. Sensitivity analysis for TPC market price by photobioreactor

Fig.13. Sensitivity analysis for TPC market price by pond approach

Fig.14 presented the sensitivity analysis for LCC and TPP of the whole plant life span. According to **Fig.14**, while TPC, Tax, SV, TBS, TBPS, all were varied with different ranges of estimations, LCC and TPP were influenced but not too much. The LCC was more than US$2,000,000 and TPP was around US$600,000 for project lifetime. Thus, by this sensitivity analysis, it was projected that the bioethanol production plant from microalgae would be feasible if microalgae growth would go as expected. Moreover, the TPP could be increased if the TEC is reduced since TEC might vary from region to region. As microalgae cultivation is environment friendly, eliminate CO_2, produce O_2 to the environment and purifies wastewater, so microalgae cultivation for bioethanol is highly recommended to integrate with heavy metal, chemical industries to reduce the environmental pollution and more economical[30].

Fig.14. Sensitivity analyses for bioethanol production from microalgae on different market price

Advantages, Limitations, Challenges and Recommendations to Microalgal-Bioethanol Commercialization

- The microalgae-bioethanol plant in Brunei Darussalam is capable to produce year-round microalgae biomass with no weather disruption since Brunei Darussalam does not contain winter season due to geographical location.

Because of being surrounded by sea and having adequate rainfall throughout the year, this region does not have a water supply problem to microalgae culture. Other study mentioned that freely available sunlight, abundant water, CO_2, nutrients, essential inorganic elements (e.g. Zn, Cu, Fe, Mn, Co, Mo and others) can reduce production cost[26]. With this view, current project is more feasible than the other previous TEA studies performed in winter based countries like European countries, Canada, USA and others. Winter based countries required extra heat and electricity cost in winter season to maintain the cultivation temperature and water temperature (prevention to transform into ice) as well as artificial UV light (alternative to sunlight)[63]. Furthermore, compared to other biofuels from microalgae, bioethanol is comparatively cheaper to produce, which is economical for the plant set up. The previous case studies of TEA from microalgae biofuel presented that biodiesel from biomass was approximately 20% higher expensive to generate than the wholesale diesel price while bioethanol was roughly 5% more expensive to produce than the wholesale gasoline price[64].

- The current TEA project presented the total production cost 2.22 million US$ for bioethanol from microalgae while the total bioethanol selling price was 2.87 million US$ with by-product selling price 1.6 million US$. Apart from by-product selling price, total production cost for microalgal-bioethanol and co-products was 11, 10,666 US$/y where total bioethanol production was 57087.62 gallon/y bioethanol with co-products: crude bio-liquid and bio-solid. This result summarized 19.45 US$/gallon bioethanol for this project, which is very high compared to other industrial TEA. Different case studies from different industries and projects presented that the production cost of microalgae-bioethanol (Algenol) can vary with different prices such as 1.27US$/gallon, 2.20 US$/gallon, 6.27 US$/gallon, 8.34 US$/gallon, 31.36 US$/gallon[63]. Therefore, the studied TEA project did not demonstrate very large profit to commercialize by private sector albeit government sector may initialize this project to address alternative biofuel production in the country as well as minimize the tremendous GHGs from the environment. But the fuel policy support through blending mandates and tax credit policies like Brazil (bioethanol from sugarcane) can be very effective to allow some variants to consumer fuel market entry. In addition, subsidies associated with biofuel accounted for the addition benefits of lower net environmental effect compared to fossil fuels and advantages from improved fuel access as well regional/national fuel independence as economic freedom for fuel purpose. Brazil, USA and some regions in Africa reduced dependence on fuel imports and increased fuel security as well as impacted on socio-economic development by opening lower-skill level job opportunities (biomass cultivation) as well as higher-skill level such as engineers, human resources for research and development. Thus, the current TEA model was encouraged to be established in Brunei[64]. Moreover, to make the microalgae-bioethanol commercialization attractive to the private sector, R &D should focus on the other microalgae species with higher yield of bioethanol and potential nano-catalyst applications on microalgae cultivation and conversion to bioethanol during fermentation. Overall, microalgal-bioethanol utilization mandated with gasoline as well as microalgae cultivation and biofuel production integrated with existing complementary industries can be a superior alternative for future applications.

- Compared to the other studies, studied TEA model has presented higher capital and production cost of bioethanol from microalgae due to the higher price of equipment and production materials in the current location. To note, all production materials and equipment in Brunei are usually imported from developing countries with high expense. Since the TEA was projected for microalgae-bioethanol production at offshore in Brunei, all costs were calculated based on this specific location. In this case, to reduce the capital and production cost, lower-cost machineries might be imported from the cheaper market in India, China, Indonesia, Malaysia and others. However, the microalgae growth yield was higher and the land cost and operating cost in this TEA project is less than other countries like USA, Australia and Canada[63, 64]. According to the case study of microalgae-biofuel commercialization, indirect cost of the current project such as engineering and supervision, construction expenses, contractors' fees were lower than the case study, legal expense was similar, working capital of FCI was higher than the case study. In the case of direct cost, cost for installation, instrumentation and controls were higher than the case studies, building cost was lower and other costs: piping and insulations, electrical facilities and yard improvements was almost similar like case studies[64]. The FCI of this project was 78% of TCI which is lower than the FCI (89%) of other algae-biofuel commercial plant albeit the working capital of this current project was, 0.09 of TCI which was higher than algae-biofuel commercial plant[65]. The variations of the current study with other studies have been occurred due to the expense difference of key components based on different regions.

Conclusions

The demand of bioethanol utilization is rising day by day as both fossil fuel blend and substitute of relic fuel due to environmental issues and quick fossil fuel depletion. Many candidates are being experimented to generate bioethanol, but most of them usually clash with human and animal food chain where microalgae turns to disturb no food chain, carry higher amounts of oil than other energy crops, clean wastewater, gasps CO_2 and emanate O_2 to the environment. Thus, it is being considered an ideal source of bioethanol production. To assess the techno-economic aspect of this application, LCC model, TPP, PP, cash-flow diagram and break-even analysis were built up and project life spanwas predicted for 20 years. It has been determined that by considering continuous O_2 supply to the environment, the TPP was US$591,333 what identified the project environment-friendly and beneficial. Even with sensitivity analysis comprising variable ranges of all influencing factors, the study is still providedto feasible indication economically. As bioethanol production from microalgae still contemporary application with modern technology, the required steps for this project should be taken care by considering all the risks related to the success of massive microalgae cultivation, machines especially PBR operation and bioethanol separation.

Acknowledgment

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Table 1

Comparison between studied species and other microalgae species in the projected location in terms of carbohydrate accumulation

Microalgae	Carbohydrate Accumulations (%)
Chlorella vulgaris	52 [28, 36]
Chlorella sokoniana	40.3 [36]
Scenedesmus obliquus	26 [36]
Tribonema sp.	31.2 [36]
Chlorococcum humicola	32 [36]

Table 2

Key Estimations for Microalgae Cultivation and Bioethanol Production[41, 51]

Key Items	Photobioreactors (PBR)	Ponds
Microalgal Biomass Productivity	56 tonnes $ha^{-1}y^{-1}$	28 tonnes $ha^{-1}y^{-1}$
Total Biomass Production	110 tonnes y^{-1} or 100000kgy^{-1}	110tonnes y^{-1} or100000kgy^{-1}
Cultivation Area (ha)	2 ha	3.94 ha
Cultivation system geometry (Single Unit)	130 aligned tube per unit, 75 tubes, tube diameter 0.05 m	975 m^2 per ponds, width 10m, length 85, depth 0.30 m
Bioethanol yield	58.90m^3ha^{-1} y^{-1}	24.94m^3ha^{-1} y^{-1}
Total Bioethanol Production	31119.49 gallons y^{-1}	25968.13 gallons y^{-1}

Table 3

Total Equipment Cost (TEC) [39, 51]

Equipment	Total Cost (US$)
Ponds	20,000
Photobioreactors (PBR)	102,000
Mixers	2,800
Pumps	27,400
Sensors	7,400
Extractor	13,000
Fermentor	15,000
Rectifier	20,000
Beer Column	43,000
Evaporator	14,000
Hydrolysis Tank	15,000
Scrubber	10,000
Others	50,000
Total Equipment Cost (TEC)	339,600

Table 4

Total Capital Investment (TCI) Calculation[39, 46]

Descriptions	Fraction of delivered equipment: Bioethanol Production from Microalgae	Calculated Values(US$)
Direct Costs		
Purchased equipment, TEC		339,600
Delivery, fraction of TEC	0.10 of TEC	33,960
Subtotal: Delivered Equipment (DE)		373,560
Purchased equipment installation	0.47 of DE	175,573
Instrumentation Controls (installed)	0.36 of DE	134,482
Piping (installed)	0.10 of DE	37,356
Electrical systems (installed)	0.11 of DE	41,091.6
Buildings (including services)	0.18 of DE	67,240.8
Yard improvements	0.10 of DE	37,356
Service facilities (installed)	0.70 of DE	261,492
Total direct costs	2.02 of DE	1,128,151
Indirect Cost		
Engineering and supervision	0.10 of DE	37,356
Construction expenses	0.20 of DE	74,712
Legal expenses	0.04 of DE	14,942.4
Contractor's fee	0.05 of DE	18678
Contingency	0.08 of DE	29884.8
Total indirect costs	0.47 of DE	175573
Fixed capital investment (FCI)		1303724
Total Cultivation Area Cost (TCAC)		200000.00
Working capital (WC)	0.40 of DE	149424
Total capital investment (TCI)		1653148

Table 5

Cost calculation of OLC, TUC, OC and MC [35, 53-55]

Cost Type	Value	Calculated Value, US\$year^{-1}	Calculated Value, US$ per project lifetime
Operating Labour Costs (OLC)	2 shifts /day, 2 operators/shift, operator rate US$7/hour	61320	1226400
Total Utility Cost (TUC)	Electricity cost US$0.08/kWh, 1000kWh/day, 365 days	28480	569600
Operation Cost (OC)	Sum of OLC & TUC	89800	1796000
Maintenance Cost (MC)	0.5% of TCI	8265.74	165315

Table 6

Raw Material Cost (RMC) [35]

Microalgae Cultivation Type	Raw Material Items	Item cost for treatment kg^{-1}, US$	Total cost for treatment kg^{-1}, US$	Total dry biomass y^{-1}, kg	RMC y^{-1}, US$	RMC for project life time
Photobioreactors (PBR)	CO_2	0.01	1	100,000	100,000	200,000
	Water	0.025				
	Nutrients (Medium)	0.01				
	Chemical Agents (Pre-treatments)	0.055				
Ponds	Nutrients (Medium)	0.01	0.3	100000	3000	80000
	Chemical Agents (Pre-treatments)	0.02				
Total Raw Material Cost (RMC)/y					US$13,000	
Total Raw Material Cost (RMC)/project lifetime					US$ 260,000	

Table 7

Market price of product and by-products[57, 66]

Items	Current Market Price (US$)
Bioethanol	2.51 $gallon^{-1}$
Crude Bio-liquid	5.00 $gallon^{-1}$
Slurry Cake (Bio-fertilizer)	3.75 kg^{-1}

Table 8

Key Simulations of Project Techno-Economical Assessment[58]

Cost Calculations	Calculated Values y^{-1}, $	Calculated Value of Project Life time, $
Total Capital Investment (TCI)	-	1,653,148
Operation Cost (OC)	89,800	1,796,000
Maintenance Cost (MC)	8,265.74	165,315
Raw Material Cost (RMC)	13,000	260,000
Total Production Cost (TPC)	111,066	2,221,315
TAX	26,074.5	521,490
Salvage Value (SV)		651,86.2
Total Bioethanol Sale (TBS)	143,290	2,865,797
Total By-Product Sale (TBPS)	80,000	1,600,000
Payback Period (PP)	0.74 year	
Life Cycle Cost (LCC)	$2,274,463	
Total Plant Profit (TPP)	$ 591,333	

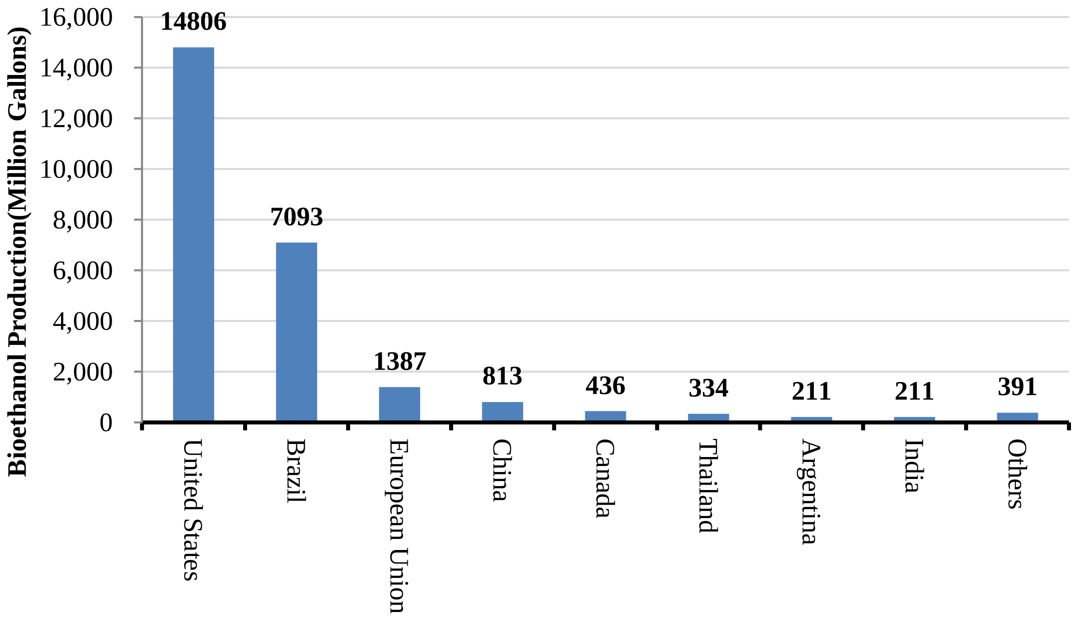


Fig.1. Worldwide Bioethanol Production in 2015[9]

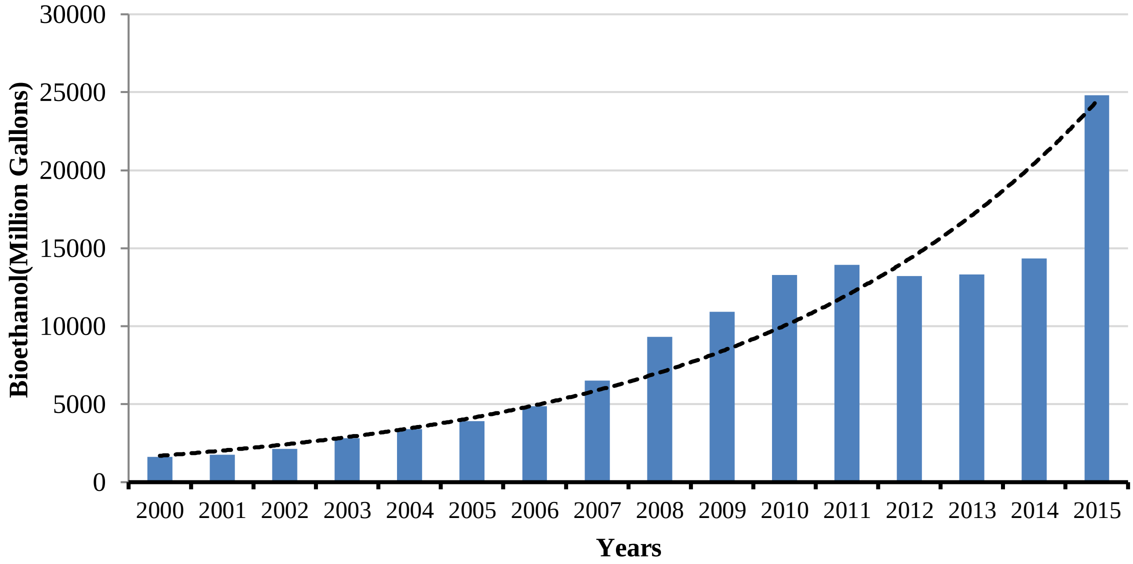


Fig.2. Bioethanol Production Rise Curve in U.S. (2000-2015)[10]

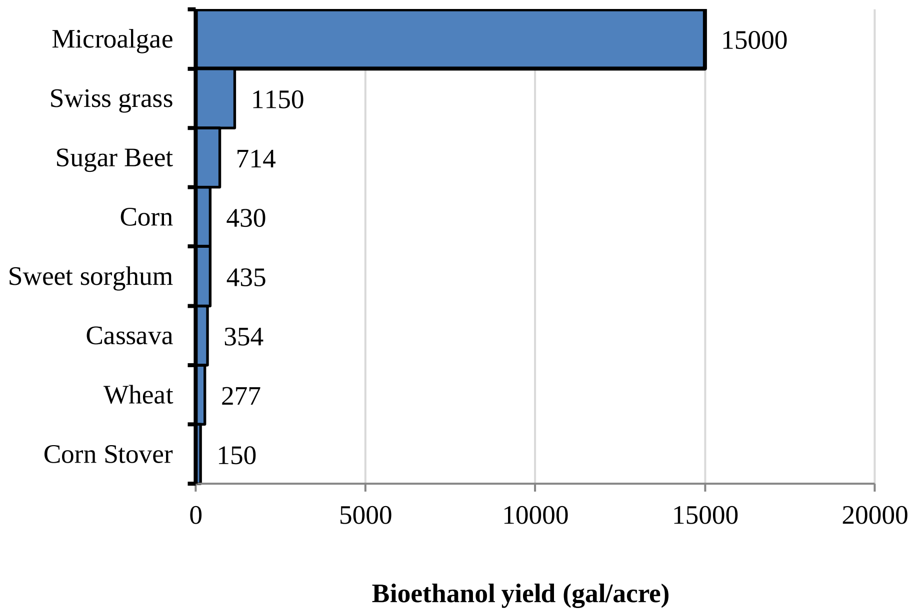


Fig.3. Bioethanol yield comparison among various sources[28]

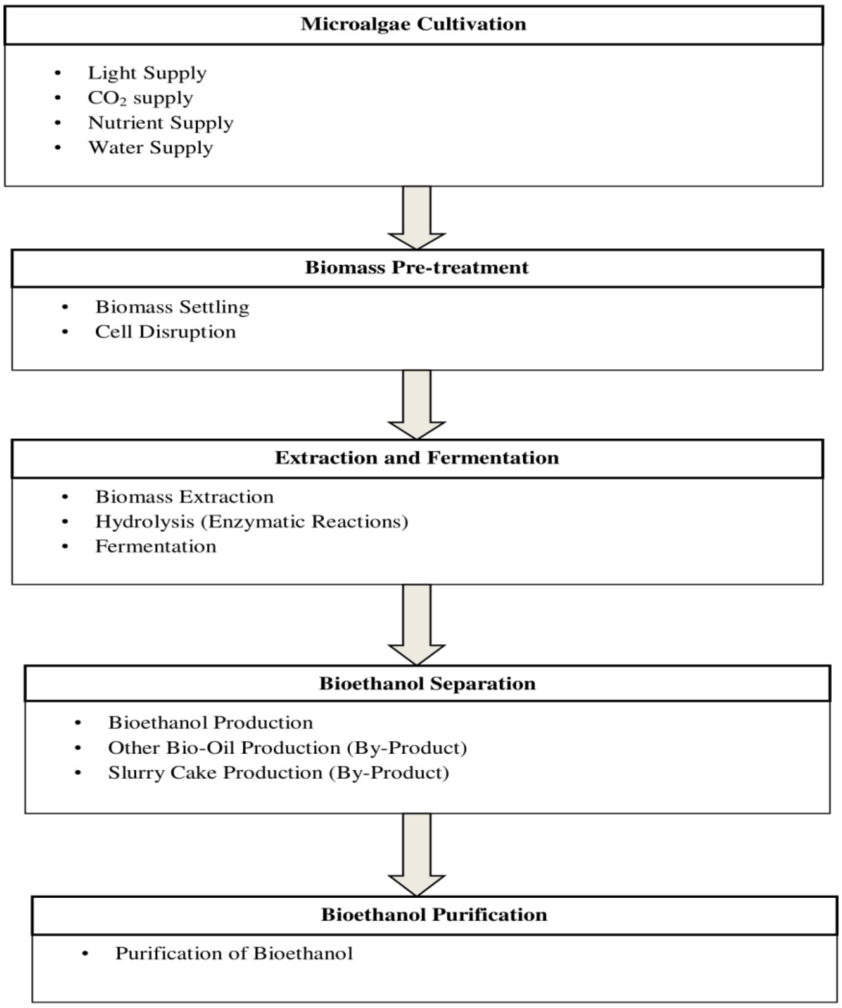


Fig.4. Technical steps for bioethanol production from microalgae[29]

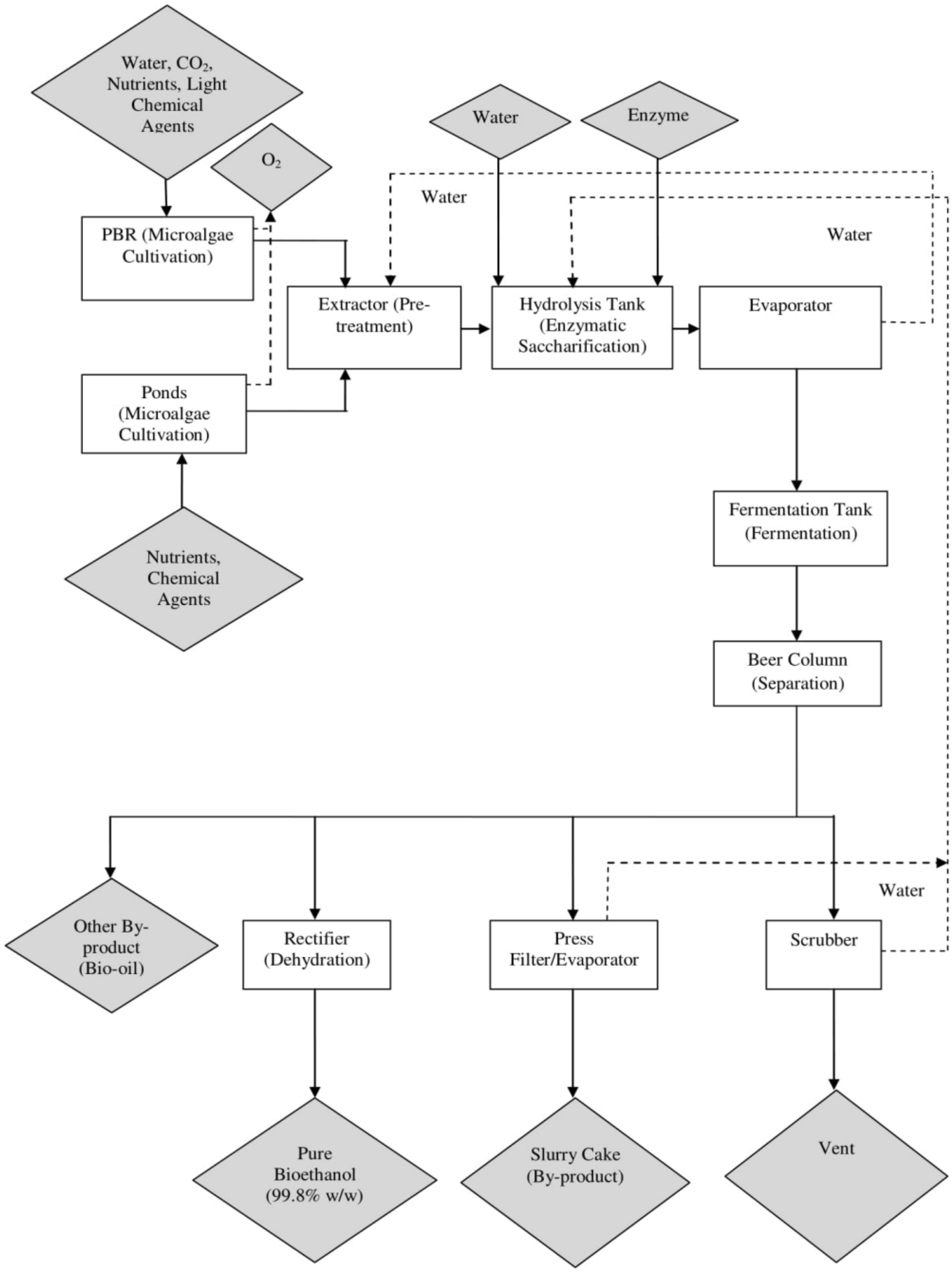
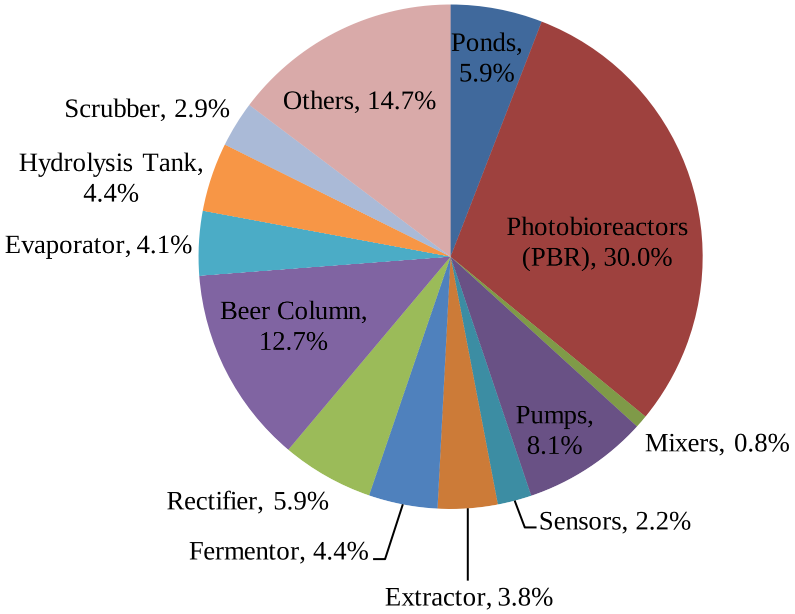


Fig.5. Technical process flow diagram of input, output and internal flows of the project



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860 **Fig.6.**Distribution of Total Equipment Cost (TEC) estimation (%)

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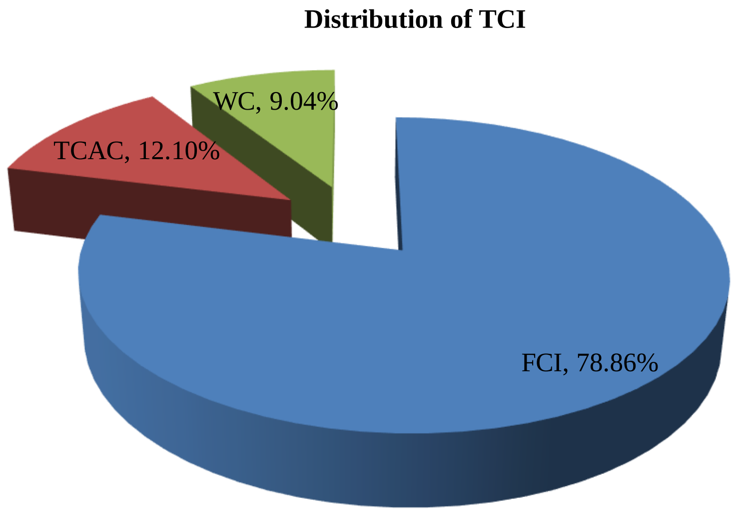

Fig.7. Distribution of Total Capital Investment (TCI)

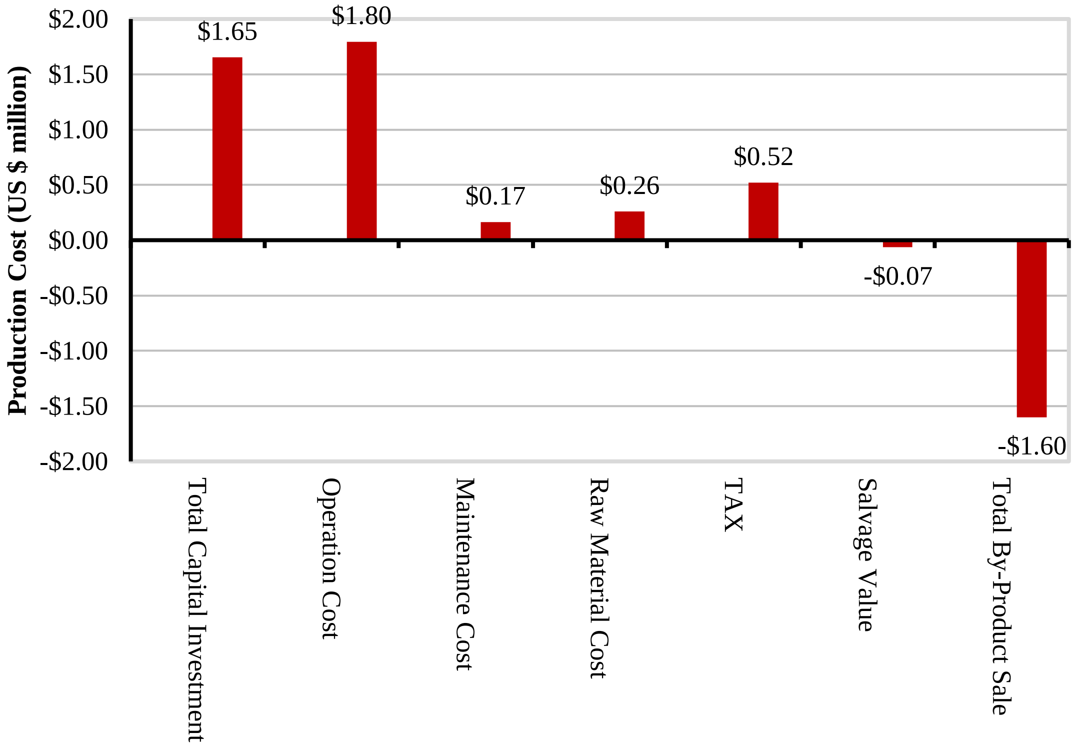

Fig.8. Distribution of bioethanol production cost from microalgae

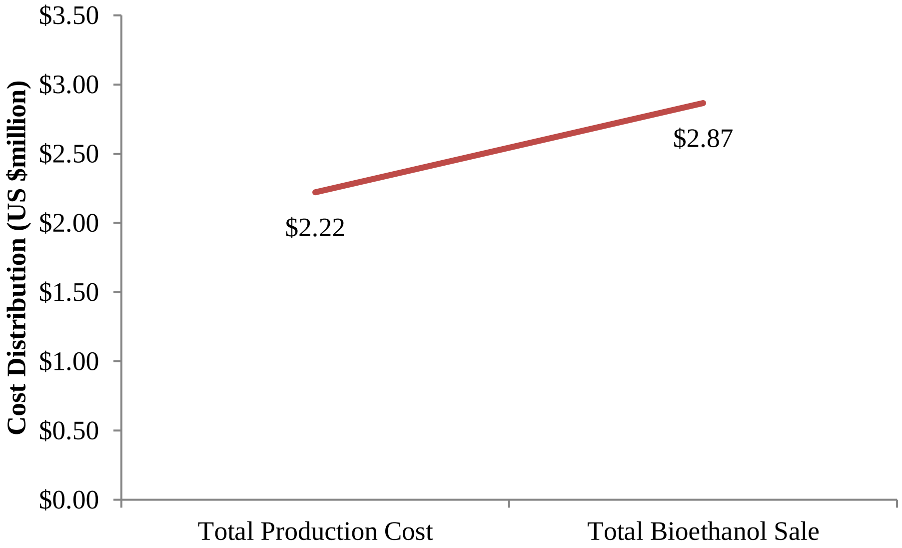

Fig.9. Bioethanol production cost vs. selling price

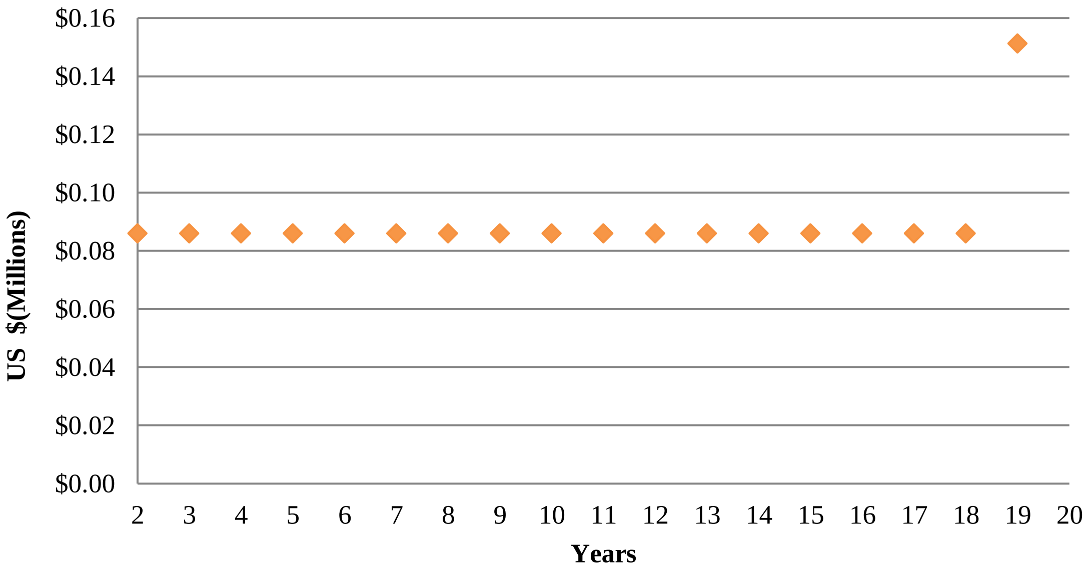

Fig.10. Yearly based process cash flow diagram in terms of total investment and income

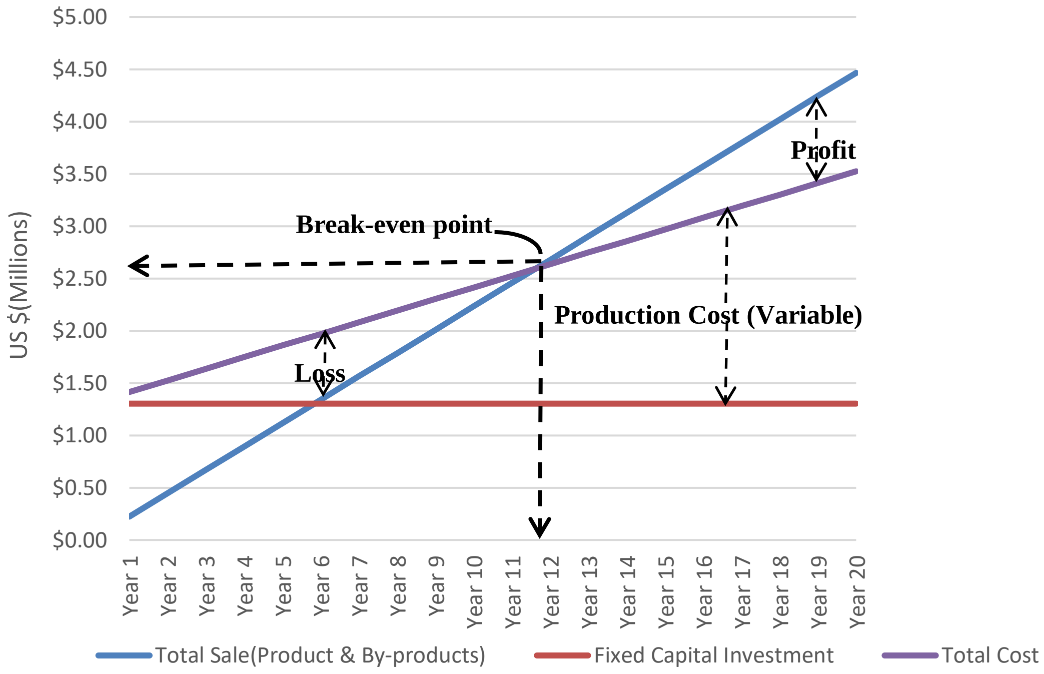

Fig.11. Break-even analysis of the bioethanol production process from microalgae

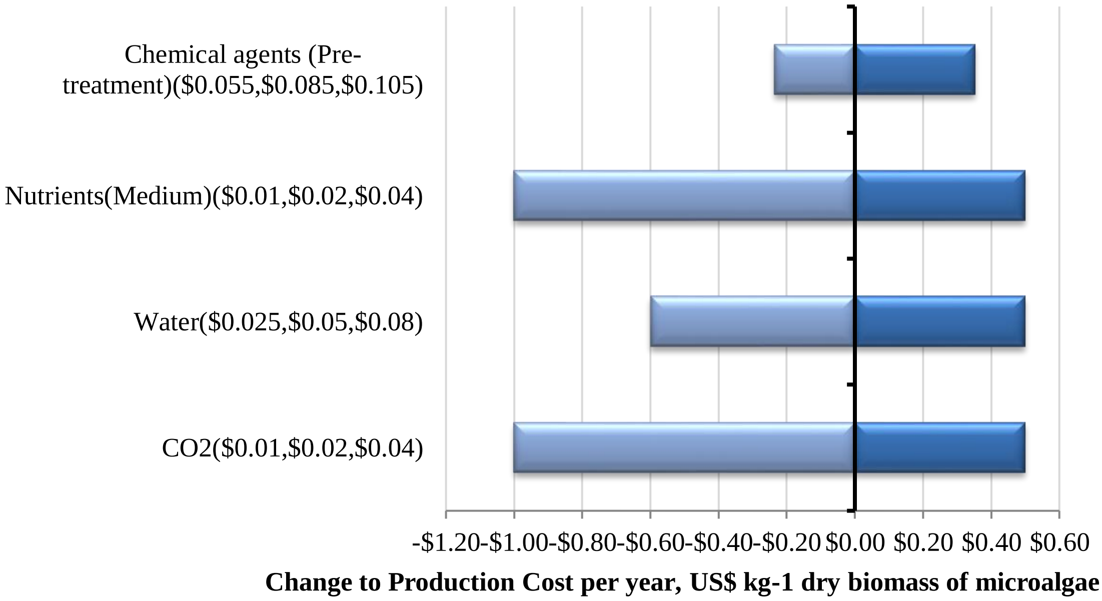

Fig.12. Sensitivity analysis for TPC market price by Photobioreactor

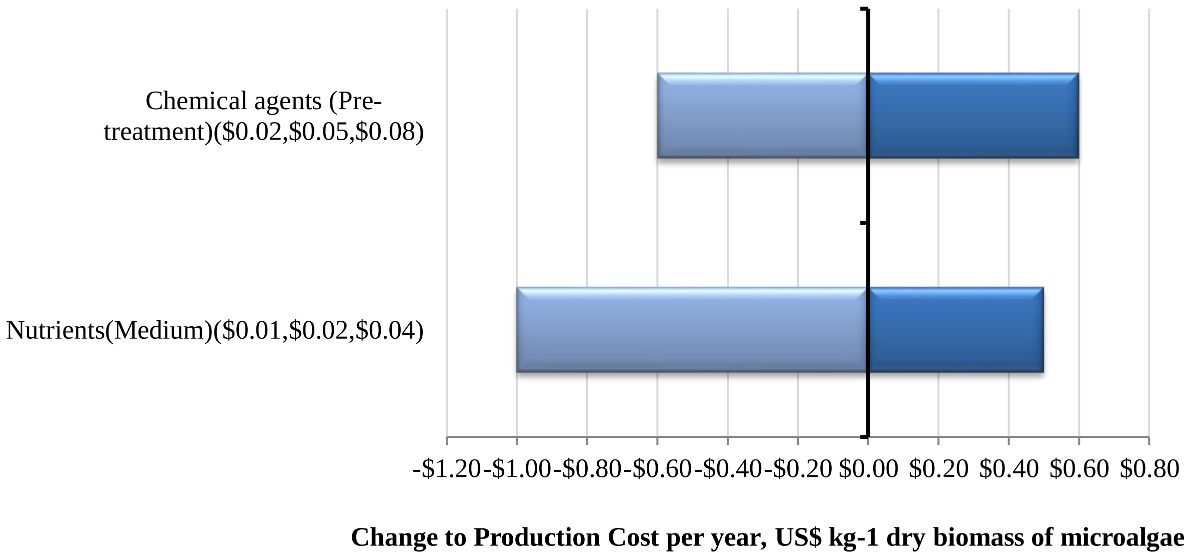

Fig.13. Sensitivity analysis for TPC market price by pond approach

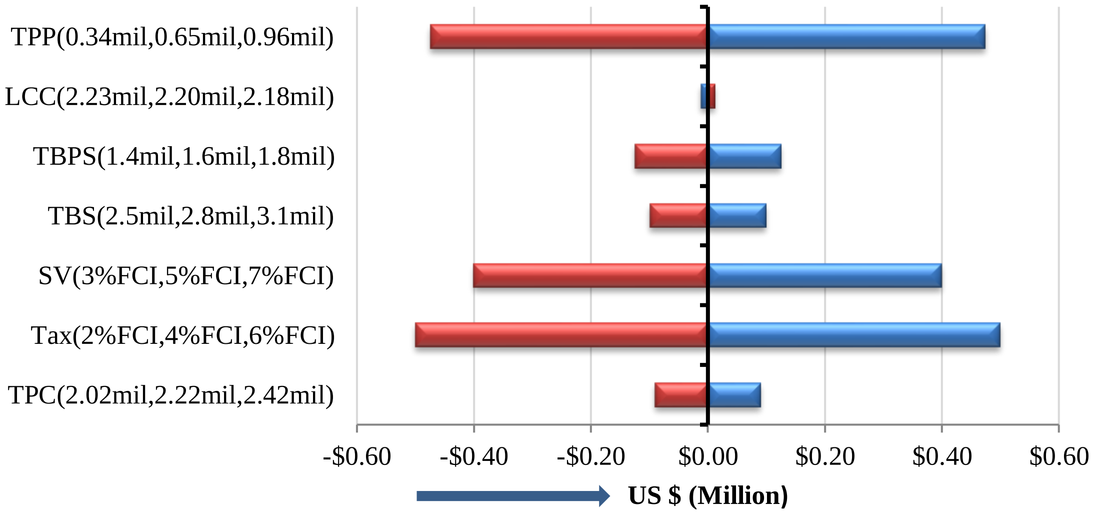

Fig.14. Sensitivity analyses for bioethanol production from microalgae on different market price