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Feasibility study of biodiesel production from microalgae grown on domestic wastewater: A case study of Egypt

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Abstract : First test diesel engines using blends with algal biodiesel are already carried out but still optimized. The purpose of microalgae growing is mainly for food and feed markets, but algal biofuel has much attention in recent years worldwide. Technical data about feasibility of cultivation system, lipids extraction and conversion into biodiesel are still limited. Potentials of microalgae have incentive the Egyptian scientists to conduct a preliminary economic assessment for 0.25 Million tons biodiesel production from microalgae grown in wastewater, which had a range of expected accuracy ±20%. Process units required have been sized. Total capital investment (TCI), total manufacturing cost (TMC), net profit, rate on return (ROR) and payback period were all calculated to be USD138134136, USD576517352, USD121584271, 88% and one year, respectively based on feedstock cost of USD400/ton and biodiesel selling price of USD2000/ton. As well, sensitivity and break-even analyses were evaluated on variations in feedstock cost, product prices and microalgae lipids content using ROR and payback time. Results recommended that for profitable algal biodiesel business, the biomass cost cannot be higher than USD530/ton, algal biodiesel price and biomass lipids content must be above USD1578/ton and 30% on dry basis, respectively.
Keywords : Algal biodiesel, transesterification, preliminary economic assessment, sensitivity and break-even analyses, rate of return.

1.0 Introduction

The energy demand is growing worldwide.[1] About 80% of the total energy consumption is delivered from petroleum, natural gas and coal with an increase in greenhouse gas emissions that must be reduced by at least 10% in 2020 according to the European Union planned targets.[2]Annual consumption of fossil-based fuels is expected to rise by approximately 90% in 2030 [3], so biofuel as a green renewable alternative can decline the global energy shortage. Algal biodiesel has recent interests; to blend by at least 5% to petro-diesel.[4]Its industrial production can be achieved via lipids extraction followed by alkaline or acidic transesterification process.[5] In-situ transesterification of biomass into fatty acid methyl esters (FAMEs) can be investigated; to cancel the extraction step[6] but still expensive.[1]

The potentials of microalgae as renewable source for feasible biodiesel production are promising; due to the capability to store more lipid amounts (20-75%wt)[7] than other oil crops like Jatropha curcas and rapeseed[8], and can be used for carbon fixation (1kg algae require 1.8kg CO_2)[9]. Algae cultivation has no competition with classical agriculture resources.[10]Algae can be grown on domestic wastewater and offer a triple facet solution: environmental, economic and waste control[11]; as to obtain 1liter of biodiesel, about 20 liters of water are required.[12]

Algal biodiesel is technically available but, non-commercial now; because of the high investments costs and the high demand on auxiliary energy for biomass production, microalgae oil "Oilgae" leaching, and biofuel manufacturing.[2] Feedstock cost is the bottleneck of biodiesel marketing on large scale; as it represents about 80% of total manufacturing cost.[13,14]Utilization of algalcake after Oilgae production for example as soil conditioner is a key factor in biorefinery concepts inorder to improve economic feasibility.[15]Furthermore, 37 kilotons of fossil diesel are consumeddaily, since 50-60% of consumption rate is imported(USD 800-1100/ton) according to the EIA (U.S. Energy Information Administration)statistics.So, in this research preliminary feasibility study is illustrated for production of 0.25 Million tons biodiesel from microalgae cultivated in wastewater; in order to blend by 5% with petro-diesel in the near future.

Process Design and Case Study

Background of the case study

Egypt diesel demand rose by approximately 30% from 2005 to 2015 according to EIA statistics. Diesel prices had been increased from October 2008 to July 2014 by 64% to record USD 230/ton (EGP 1.8/L). Policies in Egypt encourage the new investments by offering tax incentives and subsides (e.g. Project land and water), but still not appreciable for biofuel business. It is proposed to blend 5% of biodiesel with petro-diesel by 2020. To get rid of diesel shortage and save its imports by at least 5%; biodiesel plants can be constructed based on annual capacity of 0.25 Million tons and selling price of USD 2000/ton. Hence, this article presented preliminary feasibility study of biodiesel production from microalgae cultivated on domestic wastewater.

Algal oil extraction and biodiesel production

Algal lipids (polar and non-polar) are extracted using Static Solvent Methodology[16]; where the biomass was delivered to the extraction vessels and methanol as a solvent (20ml/1g algae) was added. Extraction mixture was agitated at 500rpm for 12 h. Cells' residue "algalcake" was removed by filtration throughWhatman GF/C paper, and dried at the sun. The filtrate (methanol-algal oil mixture) was fed into a reactor and heated to the specified temperature (e.g. 65°C). The catalyst (KOH) was dissolved in excess alcohol and added; to achieve the transesterification process. Once reaction has completed, the products are subjected to flash evaporation; in order to recover the excess methanol, and then transferred into a decanter; since biodiesel and glycerol layers are generated; due to the densities difference of 0.86 and 1.22 g/ml, respectively.The algal biofuel layer was washed with hot water (55°C) for 2 times; to get rid of catalyst and glycerol traces. The wastewater is then decanted, and biofuel is distilled under vacuum for purification before storing. In contrast, the crude glycerol (85% purity) is neutralized by H_3PO_4; to get rid of free fatty acids (FFA), then washing followed by distillation was performed before storing in a tank.

Design basis

Nannochloropsis sp. microalgae of 44% lipids were grown on domestic wastewater obtained from Zenein Wastewater Treatment Plant (ZWWTP), Giza governorate, Egypt.Oilgae extraction was done according to Smedes, F. &Thmasen, T.[17], as solvent/biomass ratio of 10ml/g is required to yield 73% Oilgae in 12h at ambient conditions; to avoid energy consumption. Generally, algal oils contain FFA in range of 1-19% [18], however it is less than 2% and avg. $M_{wt.}$ of 845 for *Nannochloropsis sp.* Fatty acid profile of algal methyl esters is abided the biofuel requirements and listed in Table 1. Optimization of alkaline transesterification recommended that ultimate biodiesel yield of 96.5% can be achieved using 12/1 alcohol/oil molar ratio and 2%wt/wt as KOH concentration at 65°C for 1h.[24]Schematic diagram of algal processing for biodiesel production is illustrated in Figure 1. Evaluation of algal biodiesel and its blends to fossil diesel according to EN 14214 standards are illustrated in Table 2.

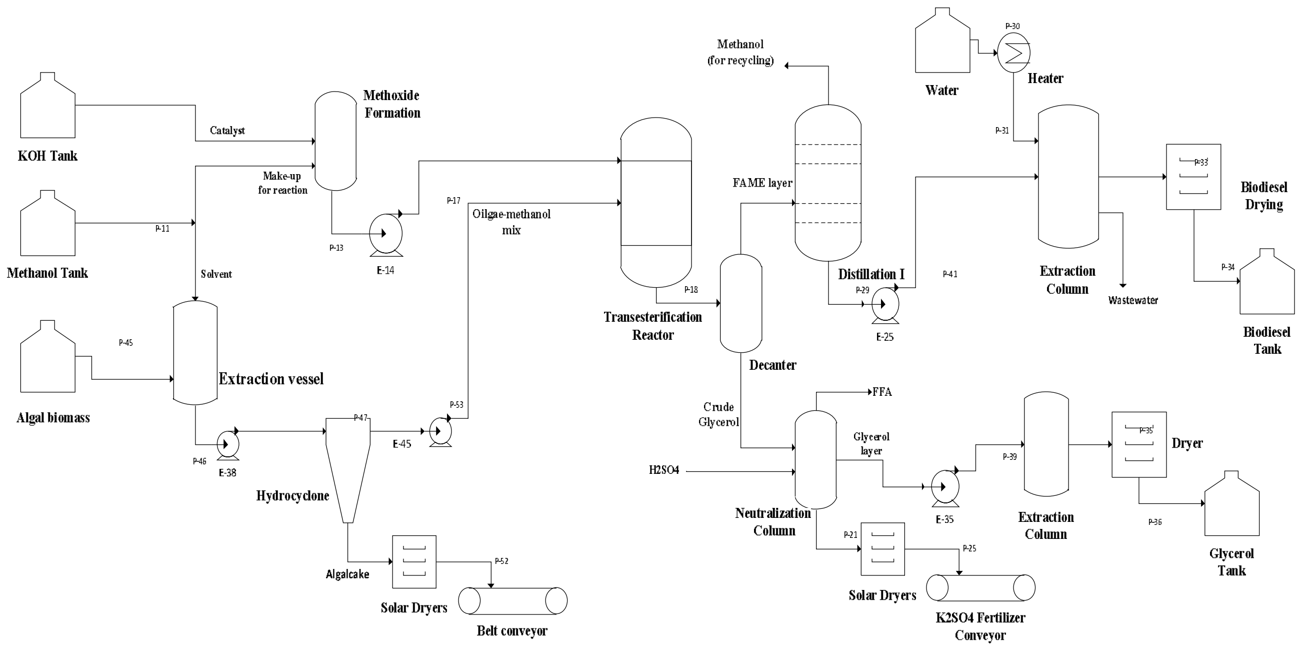

Figure 1: Schematic diagram of algal biofuel processes

Table 1 Fatty acid profile of biofuel from feasible algae strains compared to oil crops

Fatty acid methyl ester%	***Nannochloropsis sp*. Lipid %: 31-68** [19]	***Botryococcusbraunii* Lipid %: 25-75** [20]	***Spirulina platensis* Lipid %:9-12**[21]	**Jatropha *curcas* Lipid %: 29-40** [22]	**Rapeseed Lipid %: 33-43**[23]
Myristic (C14:0)	5.0	0.8	3.56	-	-
Palmitic (C16:0)	37.5	21.0	14.87	18.22	4.9
Palmitoleic (C16:1)	23.3	2.0	0.98	-	-
Stearic (C18:0)	0.9	2.9	28.11	5.14	1.6
Oleic (C18:1)	11.9	3.2	5.39	28.46	33.0
Linoleic (C18:2)	1.5	46.6	1.12	48.18	20.4
Arachidic (C20:0)	0.1	0.2	32.43	-	-
Eicosenoic (C20:1)	3.3	0.1	1.94	-	9.3
Eicosadienoic (C20:2)	15.3	-	0.99	-	-
Behenic (C22:0)	0.4	-	6.65	-	23
Lignoceric (C24:0)	-	0.2	3.96	-	-
Saturated FAME	43.9	25.1	89.58	23.36	29.5
Unsaturated FAME	38.5	5.3	8.31	28.46	42.3
Polyunsaturated FAME	16.8	46.6	2.11	48.18	20.4

Table 2 Evaluation of algal biodiesel and its blends to fossil diesel according to EN 14214 standards[21]

Property	Unit	Egyptian Fossil diesel	Biodiesel (EN14214)	Algal biodiesel (B100)	5% Biodiesel (B5)	20% Biodiesel (B20)
Density at 15°C	g/cm^3	0.8422	0.86-0.90	0.8637	0.843	0.8462
API		36.35	-	31.5	36.19	35.55
Viscosity at 40°C	cSt	1-7	3.5-5.0	12.4	4.2	5.11
Acid number	mg KOH/g oil	0.023	<0.5	0.75	0.05	0.102
Iodine number	mg I_2/100 mg oil	-	102	<120	-	-
Pour point	°C	-3	-	-9	-6	-6
Cloud point	°C	+6	-4	-3	0	0
Flash point	°C	82	>101	189	100	112
Aniline point		67	-	84	75	82
Water content	ppm	52	<500	39	45.5	40.9
Total Sulfur	%wt	0.13	<0.01	Nil	0.09	0.021
Ash	%wt	0.009	<0.02	Nil	0.0028	0.0018
Calorific value	MJ/kg	45.35	32.9	45.63	45.58	45.62
Cetane number		50	>51	70	62	68
Diesel index		48	-	67	59.69	65
Distillation temp.	°C	157		270	165	210

Results and Discussion

Economic Assessment

The feedstock is *Nannochloropsis sp.* of 44%wt lipid content and purchased cost of USD400/ton is assumed. Operating hours based on three shifts (8h) per day and 300 working days per year. The storage capacity is suggested to be one week for all materials.Glycerin and algalcake are co-products that help to minimize the annual manufacturing cost. Algalcake price is $350/ton to be proposed as bio-fertilizer.Glycerin selling price is USD750/ton according to the international market prices. Methyl alcohol recovery was 90% and 65% for lipids extraction and alkaline transesterification processes, respectively.[25]Materials flow cost accounting is presented in Table 3.

Table 3 Materials flow cost accounting

Stream	Quantity (ton/yr)	Unit cost (USD/ton)	Cost (USD/yr)
Oilgae Extraction			
Algae Feedstock	809830.5604	400	323932224.2
Methanol (solvent) requirement	8098305.604	440	3563254466
Solvent consumption (as 90% is recovered)	404915.2802	440	178162723.3
Oilgae production	258799.1718	1000	258799171.8
Algalcake	551031.3885	350	192860986
Transesterification process			
Methanol (reactant) requirement	117608.1444	440	51747583.52
Alcohol consumption (as 65% is recovered)	41162.85053	440	18111654.23
KOH (catalyst)	5175.983437	500	2587991.718
Biodiesel	250000	2000	500000000
Glycerin	25000	750	18750000
Total methanol consumption	446078.1307	440	196274377.5
Raw materials			**522794593.4**
Revenues			**711610986**

Table 4 Purchased cost of equipment (PCE)

Equipment	Unit No.	Unit cost (USD)	Total cost (USD)
Methanol storage tanks (200 m^3)	52	50000	2600000
Belt conveyor	5	22000	110000
Extraction vessels (300 m^3)	100	75000	7500000
Mixers (Propeller, 10 hp)	100	10000	1000000
Pumps (progressive cavity type, 30gallon/min)	300	11000	3300000
Filters (Hydrocyclone, 1m diameter, 25-50 m^3/h)	31	50000	1550000
KOH storage tanks (100 m^3)	5	25000	125000
Transesterification reactors (Jacketed & Agitated 100 m^3)	13	300000	3900000
Flash evaporation/Distillation columns	13	400000	5200000
Settlers/Centrifuges (bottom driven 3m diameter)	22	37000	814000
Absorption-Stripping towers (2m Diameter,20m Height)	16	500000	8000000
Algal biodiesel storage tanks (200 m^3)	30	50000	1500000
Glycerin storage tanks (100 m^3)	6	25000	150000
Purchased Cost of Equipment		**PCE**	**35749000**

The purchased cost of equipment (PCE) is calculated for each individual catalyst and illustrated in Table 4. The sizing of each piece of equipment was estimated and approximated from the continuous biodiesel production capacity per day in accordance with the feeding, reaction and discharging time intervals, and then the units number and unit cost (USD) of each specific equipment used in the processing were determined.[26]Electricity cost is \$0.1/kWh, and the electricity consumption is assumed to be 70kWh/ton algal biodiesel.[27] Working capital investment (WCI) is represent 15% of fixed capital investment (FCI); as the products are not require marketing heads. Total capital investment (TCI) and specific investment cost (SIC) that equals to TCI/biofuel capacity, are listed in Table 5. Different categories are involved in calculating the TCI.[26]

Table 5 Total capital investments (TCI)

Category		Cost (USD)
Physical Plant Cost (PPC)		
Equipment cost	100% PCE	35749000
Equipment delivery cost	10% PCE	3574900
Installation cost	20% PCE	7149800
Piping	20% PCE	7149800
Buildings	10% PCE	3574900
Utilities	15% PCE	5362350
Instrumentation & Control	15% PCE	5362350
Site Development	10% PCE	3574900
Auxiliary buildings	10% PCE	3574900
Total Physical Plant Cost (PPC)		**75072900**
Indirect Plant Cost (IPC)		
Design and Eng.	20% PPC	15014580
Contractor' fee	20% PPC	15014580
Contingency	10% PPC	7507290
Legal expenses	10% PPC	7507290
Total Indirect Plant Cost (IPC)		**45043740**
Fixed capital investment (FCI)		**120116640**
Total capital investment (TCI)		**138134136**
Specific investment cost (SIC)		**552.536544**

In order to decide the product price, manufacturing cost must be known so as to add a profit and hence get the selling price.[28]Total manufacturing cost (TMC) of algal biodiesel project was calculated in Table 6. The feedstock and utilities (Electrical distribution, air instrument and steam generation systems) contribute approximately 70-75% of total costs [29], while for biodiesel production from waste cooking oils using KOH as a catalyst, it contributed for 71% of total costs.[27] For a large scale production of algal biodiesel, the feedstock represents only 48% of TMCtherefore; biofuel production from microalgae cultivated in wastewater seems to be economical.

To evaluate the biodiesel project, some of economic indicators should be estimated such as the net profit, rate of return (ROR) and pay-back period according to "Eq. (1)-Eq.(3)". For a new investment, the minimum SRR in an established market is 15-20%, and the maximum pay-back period is around 5 years.[30]The Egyptian Government offering tax incentives for the new industries up to 10 years.However, 10% of gross earnings is accounted for taxes expenses. Cost evaluation of 0.25Mt algal biodiesel project is presented in Table 7.

Table 6 Total manufacturing cost (TMC)

Item	Unit cost	Cost (USD/yr)
Direct Manufacturing Cost (DMC)		
Raw Materials	USD1295 (feedstock), USD785 (alcohol) & USD0.02 (KOH)/ton biodiesel	522794593.4
Miscellaneous materials	10% M&O	357490
Electricity	$0.1/kWh	1750000
Shipping & Packaging	Assuming zero	0
Maintenance and operational cost (M&O)	10% PCE	3574900
Operating labor	$13500/employee/year	3375000
Supervision	15% Labor	506250
Plant overheads	50% of labor and M &O	3474950
Interest	2% PCE	714980
Rent	Plant land will be free; supplied by the Egyptian government	0
Royalties	1% revenues	7116109.86
Indirect Manufacturing Cost (IMC)		
Research and Development	5% of DMC	27183213.66
General expenses	25% of labor and M&O	1737475
Property insurance cost	5% PCE	1787450
Depreciation	Straight-line depreciation over 15 years factory life	2144940
Total Manufacturing Cost (TMC)		**576517351.9**
TMC/ton algal biofuel		**2306.069408**

Table 7 Cost evaluation of algal biodiesel industry

Item	Value
Raw materials (USD/yr)	522794593
Revenues (USD/yr)	711610986
Total capital investment (USD)	138134136
Total manufacturing cost (USD/yr)	576517352
Net profit (USD/yr)	121584271
ROR (%)	88.01
Pay-back time (yr)	0.97

$$\text{Net Profit} = \text{Total Revenues} - \text{TMC} \quad (1)$$

$$\text{ROR\%} = \frac{\text{Net Profit}}{\text{TCI}} \text{x} 100 \quad (2)$$

$$\text{Payback period (years)} = \frac{\text{FCI}}{\text{Net profit} + \text{Depreciation}} \quad (3)$$

Sensitivity Analysis

Feedstock (algae) cost is the limiting factor of biodiesel commercialization, so in the sensitivity analysis, the algae cost and biodiesel selling price are changed to decide the sustainability of biodiesel business using the rate of return (ROR) and payback time indicators. Assuming that the capital investment is recovered within the 1^{st} year and the production has only 50% of the full capacity, while the 2^{nd} year onwards rose to 100% of total production capacity. Annual increase of 10% is suggested for TMC. Assuming the biodiesel price is USD2000/ton for the variations in biomass cost, while the reference algae cost is suggested to be USD400/ton in Egypt for biofuel price changes. Lipid content is greatly important criteria to select the feasible strain. For profitable algal biofuel project, the microalgae oil content cannot be less than 30.4% to obtain ROR of 16% and payback time of 4.95 years. Sensitivity analysis results are shown in Figure 2, Figure 3 and Figure 4.

To obtain ROR>20%, the biodiesel selling price must be greater than USD 1578/ton, based on feedstock price of USD400/ton and oil content of 44%. In contrast, algal biomass cost below USD 530/ton is recommended. Sensitivity analysis indicated that biodiesel industry in Egypt can be implemented using alkaline transesterification of microalgae grown on wastewater.

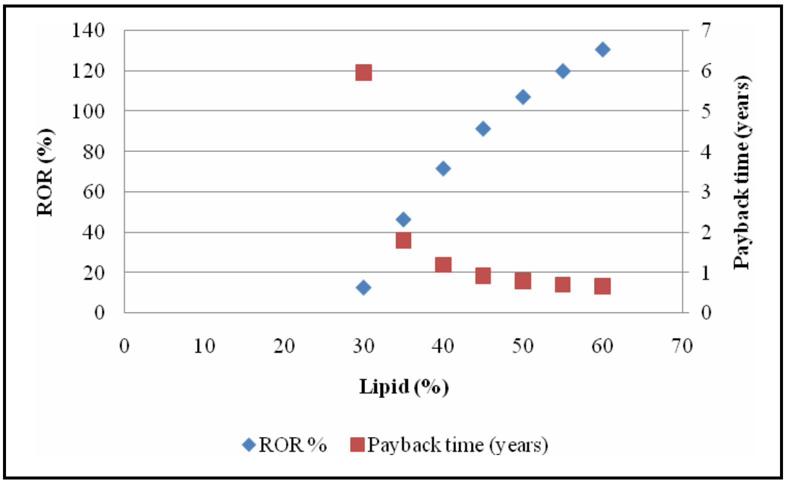

Figure 2: Sensitivity analysis with variation in lipid %

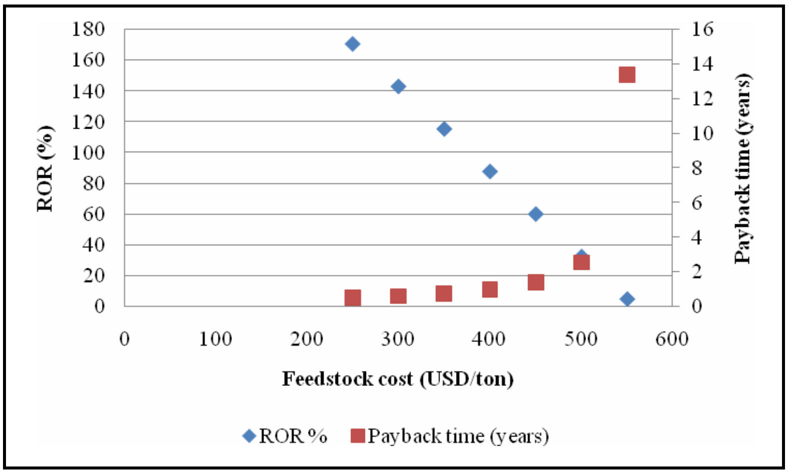

Figure 3: Sensitivity analysis with variation in feedstock cost

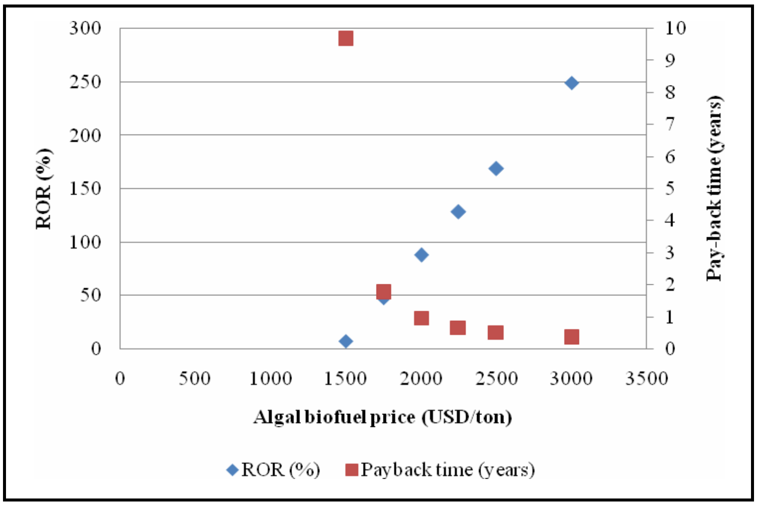

Figure 4: Sensitivity analysis with variation in algal biodiesel price

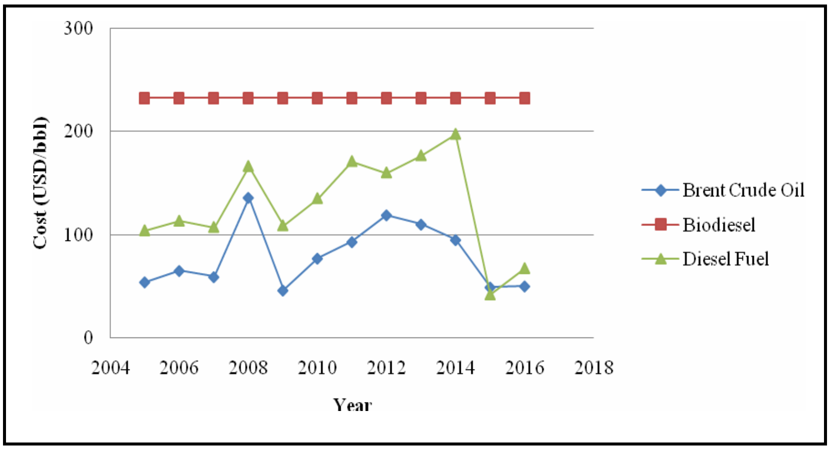

Figure 5: Break-even oil barrel chart

Break-even Analysis

Break-even analysis was performed to determine the biodiesel selling price at which no profit is fulfilled. This research work was conducted to solve part of the Egypt diesel shortage by cultivating viable microalgae strains in domestic wastewater for green fuel production. The break-even calculations reported that the minimum biodiesel price per ton is USD 1454, while *Nannochloropsis sp.*cost is fixed (USD400/ton).Crude oil prices are continuously changed; as in 2010 year, the Brent Crude Oil Spot price was USD77/barrel, and rose to USD120/barrel in 2012 then declined to USD36/barrel in December 2015 according to EIA statistics. Consequently, the standard diesel prices are changed. However, Brent Crude Oil Prices will be in range of USD40-60/barrel up to 2020 as reported by Kuwait Administrator at OPEC in January 2016. Algal biodiesel project will be feasible in Egypt if its price is below the international diesel fuel prices. Based on the monthly average prices, break-even oil barrel chart for biodiesel industry is presented in Fig 5.The biodiesel and petro-diesel prices are expectedto match when the Brent Crude Oil Spot cost is USD150/barrel in 2045 as experts guess. Therefore the algal biodiesel project is viable and feasible if the barrel standard petroleum price is above USD 150. However today, it is more economical to blend the algal biodiesel with jet fuel.[28]

Conclusions

This study presents a preliminary economic assessment of biodiesel production from *Nannochloropsis sp*. microalgae cultivated in domestic wastewater obtained from Zenien treatment plants. Results show that TCI is USD138134136, TMC is USD576517352, net profit is USD121584271, ROR is 88% and payback period is less than one year based on algal biodiesel capacity of 250 kilotons annually, feedstock cost of USD400/ton and product selling price of USD2000/ton. Lipid content more than 30% is suggested for profitable algal biodiesel business. To maintain ROR>16%, the feedstock cost cannot higher than USD530/ton and biofuel price above USD1578/ton is recommended. Algal biodiesel is not commercial now; because of the decline of Brent Crude Oil and diesel prices to USD31/barrel and USD40/barrel, respectively in Jan. 2016, but it is more profitable to export or blending with aviation fuel. However, the algal biodiesel project is viable and feasible if the barrel Brent Crude Oil Spot is above USD 150.

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References

1. El Shimi, H.I., Attia, N.K., El Sheltawy, S.T., El Diwani, G.I. Techno-economic analysis of algae-oleum production. *Int. J. Sci. Eng& Res. (IJSER)*; 2016 (1):282-289.
2. Schlagermann, P., G¨ottlicher, G., Dillschneider, R., Rosello-Sastre, R., Posten, C. Composition of Algal Oil and Its Potential as Biofuel. Journal of Combustion; 2012 (Article ID 285185), 14 pages.
3. Marchetti, J.M.,Errazu, A.F. Biodiesel production from acid oils and ethanol using a solid basic resin as catalyst. Biomass Bioenerg; 2010 (34): 272–277.
4. Amaral, M.S., Loures, C.C., Da Rós, P.C., Machado, S.A., R. Reis, C.E., Castro, H.F., Silva, M.B. Evaluation of the cultivation conditions of marine microalgae *Chlorella* sp. to be used as feedstock in ultrasound-assisted ethanolysis. Biofuel Research Journal; 2015 (7): 288-294.
5. Chisti, Y. Biodiesel from microalgae. BiotechnolAdv; 2007 (25): 294-306.
6. El-Shimi, H.I., Attia, N.K., El-Sheltawy, S.T., El-Diwani, G.I. Biodiesel Production from *Spirulina-Platensis* Microalgae by In-Situ Transesterification Process. Journal of Sustainable Bioenergy Systems; 2013 (3): 224-233.
7. Schenk, P. Second generation biofuels: high-efficiency microalgae for biodiesel production.BioEnergy Research; 2008 (1): 20-43.
8. Amaro, H.M., Guedes, A.C., Malcata, F.X. Advances and perspectives in using microalgae to produce biodiesel. AppliedEnergy; 2011 (88): 3402-3410.
9. Delrue, F., Setier, P., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., Froment, A. An Economic, Sustainability, and Energetic Model of Biodiesel Production from Microalgae. Bioresource Technology; 2012 (111): 191-200.
10. Jones, C.S., Mayfieldt, S.P. Algae Biofuels: Versatility for the Future of Bioenergy. Current Opinion in Biotechnology; 2012 (23): 346-351.
11. Moustafa, S.S., Shalaby, E.A., Mahmoud, G.I. Cultivating Microalgae in Domestic Wastewater for Biodiesel Production. Not SciBiol; 2012 (4):56-65.
12. Fraiture, C., Giordano, M., Liao, Y. Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy; 2008 (10): 67–81.
13. Chhetri, A.B., Watts, K.C., Islam, M.R. Waste cooking oil as an alternate feedstock for biodiesel production. Energies; 2008(1): 3–18.
14. Zhang, Y., Dube, M.A., McLean, D.D., Kates, M. Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. Bioresour. Technol; 2003(90): 229 – 240.
15. Raphael, S.,Ausilio, B. Microalgae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. Biomass and Bioenergy; 2013 (53): 29–38.
16. El-Shimi, H., Attia, N., Abd El-Aal, A., El-Sheltawy, S., El-Diwani, G. Quality Profile of Spirulina-platensis Oilgae Extraction for Biodiesel Production. Indian Journal of Applied Research (IJAR); 2015 (5): 16-21.
17. Smedes, F.,Thmasen, T. Evaluation of the Bligh & Dyer lipid determination method. Marine Pollution Bulletin; 1996(32): 681-688.
18. Halim, R., Danquah, M., Webley, P. Extraction of Oil from Microalgae for Biodiesel Production: A Review. Biotechnology Advances; 2012 (30): 709-732.
19. Huerlimann, R., Nys, R., Heimann, K. Growth, lipid content, productivity, and fatty acid composition of tropical microalgae for scale-up production. Biotechnology and bioengineering; 2010 (107): 245–257.

20. Zhila, N.O., Kalacheva, G.S., Volova, T.G. Effect of salinity on the biochemical composition of the alga BotryococcusbrauniiK¨utz IPPAS H-252.Journal of Applied Phycology; 2010 (1): 1-6.
21. Mostafa, S.M., El-Gendy, N.S. Evaluation of fuel properties for microalgae *Spirulina platensis* biodiesel and its blends with Egyptian petro-diesel. Arabian Journal of Chemistry; 2013
22. El Diwani, G., Attia, N., Hawash, S. Development and evaluation of biodiesel fuel and by-products from jatropha oil. Int. J. Environ. Sci. Tech; 2009 (6): 219-224.
23. Ramos, M.J., Ferna´ndez, C.M., Casas, A., Rodr´ıguez, L., P´erez, A. Influence of fatty acid composition of raw materials on biodiesel properties. Bioresource Technology; 2009 (100): 261–268.
24. Chen, L., Liu, T., Zhang, W., Chen, X., Wang, J. Biodiesel production from algae oil high in free fatty acids by two-step catalytic conversion. Bioresource Technology; 2012 (111): 208–214.
25. Nagarajan, S., Chou, S., Cao, S., Wu, C., Zhou, Z. An Updated Comprehensive Techno Economic Analysis of Algae Biodiesel. Bioresource Technology; 2012.
26. Peters, M.S.,Timmerhaus, K., West, R.E. Plant Design and Economics for Chemical Engineers, 5th ed.; McGrawHill: New York, NY, USA, 2002.
27. Karmee, S.K., Patria, R.D., Lin, C.S. Techno-Economic Evaluation of Biodiesel Production from Waste Cooking Oil—A Case Study of Hong Kong. Int. J. Mol. Sci.; 2015 (16): 4362-4371.
28. Abdo, S.M., Wahba, S.Z., Ali, G.H., Abo El-Enin, S.A., El-Khatib, K.M., El-Galad, M.I., El Diwani, GI. Preliminary economic assessment of biofuel production from microalgae. Renewable and Sustainable Energy Reviews; 2015.
29. Moustafa, H.A. Process Economics, Chem. Eng. Dept. Cairo Univ. Academic Press, 2015.
30. Skarlis, S., Kondili, E.,Kaldellis, J.K. Small-scale biodiesel production economics: A case study focus on Crete Island. J. Clean. Prod.;2012(20): 20–26.

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