ISSN 2229-5518

Techno-economic Analysis of Algae-oleum Production

Hassan I. El Shimi, Nahed K. Attia, Guzine I. El Diwani, Shakinaz T. El Sheltawy

Abstract—Algal biodiesel "or algae-oleum" has recent interest worldwide due to the unique benefits of microalgae and the extra need to biofuels. Researchers have challenges in optimizing the algal biodiesel processes. In the present work, a material balance was performed for acid catalyzed in-situ transesterification of 10,000 t/ yr biodiesel production from Chlorella vulgaris microalgae based on the previously optimized conditions as no further discussion will be presented here. A techno-economic analysis for the production processes of 10,000 t/ yr algae-oleum was introduced to investigate the sustainability and profitability indicators of the plant production capacity. A comparison between acid catalyzed in-situ transesterification and alkali transesterification of algal biodiesel was presented. The techno-economic analysis showed that infeasibility algae-oleum production via in-situ process because of the huge consumed alcohol amountsand the high cost of raw materials; as the total capital investment of $802,220, annual manufacturing cost of $36,027,960 and no earnings were fulfilled on the basis of algal biomass price of $400/ t and biodiesel price to Jet Fuel Blend of $1875/t. Successful results for conventional production approach were reported; total capital investment of $1,093,398, annual manufacturing cost of $25,845,412 and gross profit/ yr of $550,600 with high percentage simple rate of return (%SRR) of 45.3%.

Keywords— Algal biodiesel, Chlorella vulgaris, in-situ, material balance, profitability indicators, techno-economic analysis, transesterification.

1 Introduction

Biodiesel has an international interest world wide in recent years [1-4]. It made from vegetal oils (edible or non-edible) using an alcohol and a catalyst; base [5-9], acid [10-11] or enzymes [12-15]. Microalgae are a promising feedstock for biodiesel synthesis [16-19]; as they can grow in saline or wastewater[20] and a lot of strains have high oil content [21] without food competition [22]. Biodiesel production from microalgae is performed through one of the three famous protocols. The first, oil extraction by mechanical press followed by organic solvent leaching, and then convert to biodiesel via transesterification reaction [23-27]. The second is, bio-oil production from algal biomass using thermal cracking 'pyrolysis' methodology, then fractionation of this oil to biodiesel [28-30], but it is expensive due to the high energy consumption [31]. The third protocol is simultaneous oil extraction and biodiesel synthesis via in-situ transesterification 'reactive extraction' process. This method involves lipids extraction by an alcohol from algae cells, and catalyzed by the acid to produce fatty acid alkyl esters (FAAE), biodiesel [20, 32-34]. It could reduce the use of reagents and hence minimize the production cost [1,2].

There is a lot of engineering parameters play important roles in optimizing the process such as reaction time and temperature, catalyst concentration and also alcohol-to-oil molar ratio [20]. In-situ transesterification process was demonstrated by many researchers on different oilseeds [2-33] and also on different algal strains like Spirulina[1, 35], Chlorella vulgaris [36, 37] andChaetocerosgracilis [38]. Up to this moment, biodiesel production is not benign due to the high cost of feedstock, its availability and completely know-how of bio-fuel manufacturing isn't enough because of the absence of economical benefits for the project. Techno-economic analysis for biodiesel production by in-situ process of rapeseed was presented [2], the authors studied various parameters that affecting the process conversion, they recommended that 720:1 methanol-to-rapeseed oil molar ratio and 0.02 N catalyst concentration at 65ºC for 1 h is enough to yield 90% biodiesel. The study showed that total capital investment of $16,065,000, annual gross profit of $14,630,300 and simple rate of return (%SRR) was 79.5% estimated for constant price of biodiesel ($945/t) on the basis of 50,000t/yr plant capacity [2]. As mentioned previously, a lot of researchers studied the in-situ processing on different algae species [35-38], but to our knowledge, there is no published papers for detailed feasibility studies for algal biodiesel project, just Silva *et al.,* [39] studied transesterification of various algae strains using the Catilin T-300 acid catalyst and he report that, based on 20% rate of return, the estimated triglyceride purchase price was very close to the diesel wholesale price, clearly, to obtain diesel, his process adds a small increment to the cost of triglycerides [39].

The objectives of the present work were: (1) to study the techno-economic parameters of algae-oleum (algal biodiesel) production by acid catalysis in-situ transesterification processing ofChlorella vulgarisbiomass using the optimum conditions in [37]as no further discussion will be presented here, (2) to achieve a material balance for industrial scale production of 10,000 t/yr algal biodiesel based on experimental data, and (3) to compare between in-situ methodology and the conventional one optimized by Chen *et al.,* [40] for biodiesel production from microalgae.

2 Experimental work

2.1 Materials

Available biomass of Spirulina-platensismicroalgae used were cultivated and produced by business man in Zagazig City and supplied by Microbiology Department at Agricultural Research Centre (ARC) of Egypt. From our previous work [1, 23], the microalgae were analyzed to deduce the oil content by a Spectrophotometric method published in [41]. The lipids percentage of any algal strain is highly dependent on the microalgae specie and the specific growth conditions [42] which may be optimized to enhance the biofuel production from microalgae [43].Characterization of Spirulina-platensis on dry weight basis of the present work compared to data in literatures [44, 45] is illustrated in Table 1.

Methanol (CH3OH) of 99.9% analytical reagent, Hexane (C6H14) of 99% analytical grade and Sulphuric acid (H2SO4) of 98% concentration as a catalyst. All chemicals and reagents were purchased from El-Nasr Pharmaceutical Chemicals Company (ADWIC), Egypt.

TABLE 1

BIOCHEMICAL ANALYSIS OF SPIRULINA-PLATENSIS MICROALGAE

Constituent	% Composition from the present work [23]	% Composition from data in literature [44-45]	
		Mean	Std. Dev.
Proteins	62.3	62.7	0.28
Carbohydrates	12.8	16.7	2.76
Fats (Lipids)	11	6.3	3.23
Minerals (Ash)	6.95	8.3	0.95
Moisture	1.5	2.3	0.56
Fibers	4	2.8	0.85
Nucleic Acid	1.45	0.9	0.39

2.2 Experimental procedure for algal biodiesel production

Algal oil was extracted using the best conditions published in [23]; to determine the lipids content and identify the fatty acid profile. Then, acid catalysis in-situ transesterification process was the choice for algal biodiesel production due to the high viscosity and free fatty acid content (FFA) of Spirulina-platensis[1]. Experimental procedure is presented in [1, 20]. The optimum engineering conditions that affecting the biodiesel yield are presented in Table 2, compared to other research work. The yield conversion of algae-oleum in the present work was estimated based on the biomass lipids content, taking into considerations experimental and analytical error of ±5%.

TABLE 2

OPTIMUM CONDITIONS FOR ALGAE-OLEUM PRODUCTION

A, Scenedesmus sp.

Operating parameter	Conven-tional method-ology [40]	In-situ transesterification			
		The present work [20]	Literatures data		
			[36]	[37]	[38]
Algae strain	A	B	C	D	E
Lipid % wt.	28	11	30	27	20
Temp. ºC	65	65	60	80	60
Time, h	0.5	8	8	0.5	1.25
Catalyst type	KOH	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Catalyst conc. % wt/ wt oil	2	100	100	2.4 % v/ v methanol	0.35: 1 molar ratio H_2SO_4: oil
Oil/methanol molar ratio	1:12	1:3714	1:315	0.05 lit/ g algae	1:600
Stirring rate, rpm	500	650	-	-	-
Biodiesel yield %	96.6	84.7	-	82	94

B, Spirulina-platensis
C, Chlorella
D, Chaetocerosgracilis
E, Chlorella vulgaris

3 RESULTS AND DISCUSSION

3.1 Fatty acid composition of algal biodiesel

Fatty acids' analysis of microalgae oils or algal biodiesel is generally required; to confirm the feasibility of this feedstock for biodiesel production. Table 3 illustrates the comparison between the fatty acid composition of algae-oleum from Spirulina-platensis used and data found in literature[40, 46]. The predominant fatty acid groups in Spirulinaspecie are C16:0, 49.58%wt of the total fatty acidsandC14:0 represents 22.67%wt. fatty acid profile depends on the type of algae specie and cultivation conditions [47]. For biodiesel-fuel production, shorter chain and saturated fatty acids are preferred due to the lower melting points, high oxidative stability and higher Cetane numbers. However, the dominance of saturated fatty acids in Spirulina(78.87%wt) makes it a promising feedstock for biodiesel fuel production. The produced biodiesel is suggested to blend with the jet fuel outside of Egypt; to enhance the national income.

ISSN 2229-5518

TABLE 3

FATTY ACID PROFILES OF ALGAL BIODIESEL

Fatty acid	% Composition of the present work [20]	% Mean composition from data in literatures [40, 46]
Mystic (C14:0)	22.67	5.69
Palmitic (C16:0)	49.58	23.48
Palmitoleic(C16:1)	2.75	18.55
Stearic (C18:0)	5.56	1.64
Oleic (C18:1)	2.24	19.05
Linoleic (C18:2)	5.03	6.45
Linolenic(C18:3)	7.41	6.63
Ecosanoic (C20:0)	1.06	8.41
Eicosic (C20:1)	3.69	2.23
Others	0.01	7.87
Saturated	78.87	39.22
Mono-unsaturated	8.68	39.83
Poly-unsaturated	12.44	13.08

3.2 Physicochemical properties of algae-oleum

Table 4 summarize the most important technical properties of biodiesel derived from Spirulina-platensis biomass whose composition profile was discussed and presented in Table 1 and Table 3.

TABLE 4

TECHNICAL PROPERTIES OF ALGAL BIODIESEL DERIVED FROM SPIRULINA

Property	Biodiesel (Present work)	Literature data [40, 48] Mean value	Biodiesel (EN 14214 limits)
Flash point, °C	172	166	Min. 101
Cloud point, °C	5	Nil	-
Pour point, °C	-1	Nil	-
Specific gravity @ 15°C	0.886	0.861	0.86-0.90
Viscosity, mm^2/s @ 40°C	4.8	4.35	3.5-5.0
Acid value, mg KOH/g Oil	0.65	0.47	Max. 0.8
Cetane no.	61	58.5	Min. 51
High heating value, MJ/kg		39.8	Min. 35
Sulfur content, ppm	Nil	0.04	Max. 0.02

3.3 Mass balance

Based on the best reaction conditions that illustrated in Table 2, a mass balance for small industrial scale of 10,000 t biodiesel produced from Chlorella vulgaris microalgae via in-situ transesterification process was achieved for the highest yield of 94% and shown in Fig 1. Spirulina are infeasible feedstock for biofuel generation due to its low oil content (Max.11%wt) but, it is a promising ingredient for fish and poultry diet; because 60% of its biomass is proteins [23]. As a result, 10,000 t biodiesel needs 53,192 t algae biomass which contains 20%wt oil.

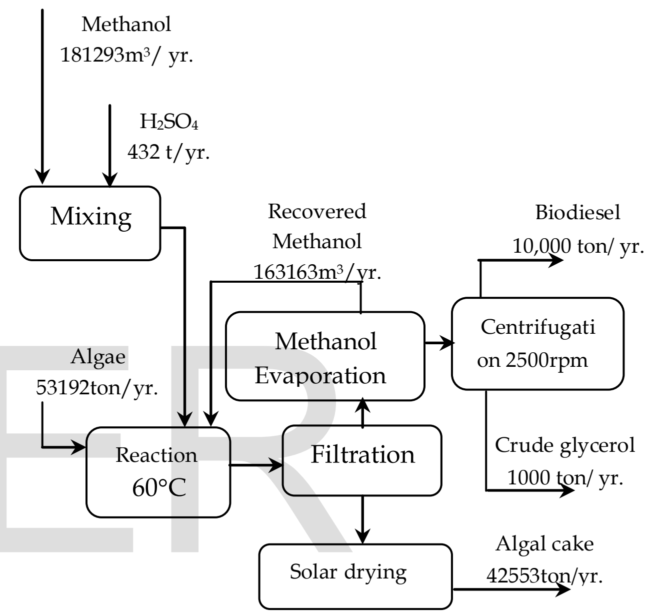

Fig. 1. Industrial scale material balance flow chart for algae-oleumproduction via in-situ transesterification.

3.4 Techno-economic cost analysis

Based on practical work on lab scale for algal biodiesel synthesis, optimum process conditions were used to evaluate all capital and operating costs for the overall production process. Biodiesel industrial scale shown in Fig 1 has been investigated for process techno-economic analysis. The cost evaluation of this study is based on the following assumptions: the plant capacity of algal biodiesel production was 10,000 t/ yr., Chlorella vulgaris biomass used as the feedstock costing \$400/t [49]. Operating hours based on three shifts (8h) per day and 300 working days per year. The storage capacity is two weeks for algal biomass and one week for biodiesel.

Depreciation estimated using straight line method for 15 years life span and the scrap value is estimated to be 10% of equipment cost. Glycerol and cake are by-products that help to reduce the manufacturing cost. Cake can be used a protein-meal for livestock or as poultry/fish diet feeding($300/t)[50]. The economic evaluation was performed on the basis of continuous algae-oleum production. From economical analysis, in-situ acidic transesterification requires huge amounts of reacting alcohol that leading the algal biodiesel project to be rejected. Recycling of methanol to process is of great importance to reduce the cost of alcohol consumption and also increase the efficiency of biodiesel product. Percentage of methanol recovery is estimated to be more than 90%wt [2]. Annual raw materials purchase cost, products and co-products sell cost are shown in Table 5. Equipment size and cost have been estimated based on the mass production from [51, 52] using cost indices of 2015 as listed in Table 6. Annual operating labor and all utilities costs are presented in Table 7 and Table 8 respectively. The techno-economic analysis indicators for the in-situ and conventional methods are listed in Table 9. The net profit is found to be $550,600 for the conventional method based on taxes-free, but no profit is recommended for the in-situ method; due to the huge methanol quantity needed for this methodology (600:1 methanol/oil molar ratio), in addition to the high cost of raw materials. In-situ transesterification had been demonstrated to be an effective method for biodiesel production from rapeseed[2]; as the gross profit was $14,630,300 based on 50,000t/yr. production capacity, but the feedstock cost was estimated to be $250/t seeds [2].

TABLE 5

ANNUAL RAW MATERIALS PURCHASED COST, PRODUCTS AND CO-PRODUCTS SELL COST

Feed	Unit cost ($/t)	Amount (t/yr.)	Cost ($/yr.)
Algal biomass	400	53,192	21,276,800
Methanol	440	2,3750.9	10,450,396
H2SO4	1,500	432	648,000
Total			**32,375,196**
Product	**Unit price ($/t)**	**Amount (t/yr.)**	**Revenues ($/yr.)**
Biodiesel	1,875	10,000	18,750,000
Crude glycerol	1,200	1,000	1,200,000
Algal cake	300	42,553.6	6,319,209.6
Total			**26,269,209.6**

Simple rate of return (%SRR) was estimated to be 45.3% for the algal biodiesel production by conventional method, which is exceeded the SRR range of new investments (15-20%), based on constant prices of biodiesel to blend with jet fuel($1875/t), algal cake as a fish diet feeding ($300/t) and glycerol for pharmaceutical use ($1200/t).Biodiesel sell cost was investigated based on the export prices and the current jet fuel cost, since biodiesel prices in the United Kingdom is ranged from $6.5 to $13 per gallon[53]. Algal biomass has unique uses in pharmaceutical and foods applications that are more expensive than biofuel prices, so it is preferred to cultivate and produce algal biomass to obtain high profit rather than using it as a biofuel source. Another suggestion, algae can be used as source for jet bio-fuel production.

TABLE 6

Equipment cost

Equipment	No. of units	Price, $
Reactor	2	90,000
Biodiesel cake separator (Filter press)	1	15,000
Methanol distillation tower	1	60,000
Biodiesel glycerol separator (Filter press)	1	15,000
Centrifugal pumps	10	54,000
Loading/unloading stations	1	25,000
Subtotal processing		**259,000**
Storages		
Methanol storage tank	1	16,000
H_2SO_4 storage tank	1	9,000
Algal biomass storage tank	1	10,000
Biodiesel storage tank	1	16,000
Crude glycerol storage tank	1	9,000
Cake storage tank	1	8,000
Subtotal storage facilities		**68,000**
Utility equipment		
Electrical distribution system		40,000
Steam generation system	1	28,000
Instrument air system		18,000
Subtotal utility equipment		**86,000**
Installation @ 45% of equipment costs		**116,550**
Total equipment cost		**443,550**
Depreciation based on 15 yr life span		**19,620**

TABLE 7

ANNUAL OPERATING LABOR COST

Labor	No. of operators per shift	Shifts per day	Operator rate ($/h)	Annual operating labor cost, $
Engineers	2	3	2.2	31,680
Supervisors	1	3	1.7	12,240
Administration	3	3	1.35	29,160
Laborer	5	3	1.35	48,600
Total				**121,680**

TABLE 8

UTILITIES' COST

Utility	Unit cost	Cost units	Utility requirement	Units of requirement	Annual utility cost, $
Electricity	0.09	\$/kWh	500,000	kWh/yr	45,000
Sat. Steam, 8 bar	7	\$/ t	10,000	t/yr	70,000
Process water	0.1	\$/ m^3	750,000	m^3/yr	75,000
Total					**190,000**

TABLE 9

TECHNO-ECONOMIC INDICATORS FOR ALGAL BIODIESEL PRODUCTION

Indicator	In-situ	Conventional
Annual cost of raw materials	32,375,196	22,902,227
Annual operating labor costs	121,680	192,240
Annual utility cost	190,000	312,000
Total equipment cost	443,550	724,100
Depreciation for 15 yr life span	19,620	25,080
Total capital investment	802,220.16	1,093,397.76
Total annual manufacturing cost	36,027,960.11	25,845,411.51
Annual revenues	26,269,209.6	26,396,011.9
Net profit	– 9,758,750	550,600
%SRR	–	45.3
Pay-back period, yr	–	1.89

4 CONCLUSIONS

In-situ transesterification has demonstrated to be an ineffective technique for biodiesel production from microalgae, especially if the lipids content of the used strain is low like Spirulina. This research was designed to analyze the techno-economic aspects of in-situ and conventional methods for algae-oleum production. Material balance to produce 10,000t/yr of biodiesel was developed. The techno-economic analysis shows that, the total capital investment for conventional method is $1,093,398 and for the in-situ method is $802,220; due to the additional algal oil extraction unit, net profit/year is $550,600 corresponding to %SRR of 45.3% and less than two years as a pay-back period for the conventional method, whileno profit is reported for the in-situ method; because of the high purchase cost of raw materials and huge alcohol consumption. This paper signs the in-situ method as a negative result in algae-oleum production; to save the research time and cost. It is more profitable to produce algal-fuel by using the alkaline-transesterification method, and then investigate thebiomass-cake infish/poultry diet food purposes.

REFERENCES

[1] H. I. El Shimi, N. K. Attia, S. T. El Sheltawy and G. I. El Diwani, "Reactive Extraction Processing of Spirulina-platensis Microalgae to produce Biodiesel: Kinetics Study". International Journal of Engineering Science and Innovative Technology (IJESIT),Vol. 4, pp. 338-349, 2015.

[2] S. A. Abo El-Enin, N. K. Attia, N. N. El-Ibirai, G. I. El-Diwani and K. M. El-Khatib, "In-situ transesterification of rapeseed and cost indicators for biodiesel production". El-Sevier Renewable and Sustainable Energy Reviews, Vol. 18, pp. 471-477, 2013

[3] Lin Chen, Tianzhong Liu, Wei Zhang, Xiaolin Chen and Junfeng Wang, "Biodiesel production from algae oil high in free fatty acids by two-step catalytic conversion", El-Sevier Bioresource Technology, Vol. 111, pp. 208–214, 2012.

[4] K. Ramezani, S. Rowshanzamir and M. H. Eikani, "Cas- tor oil Transesterification Reaction: A Kinetic Study and Optimization of Parameters," Energy, Vol. 35, No. 10, pp. 4142-4148, 2010. doi:10.1016/j.energy.2010.06.034

[5] D. M. Huang, H. N. Zhou and L. Lin, "Biodiesel: An Alternative to Conventional Fuel," Energy Procedia, Vol. 16, Pt. C, 2012, pp. 1874-1885. doi:10.1016/j.egypro.2012.01.287

[6] A. Demirbas, "Biofuels Securing the Planet's Future Energy Needs," Energy Conversion and Management, Vol. 50, No. 9, 2009, pp. 2239-2249. doi:10.1016/j.enconman.2009.05.010

[7] V. K. Wermelinger, S. Araujo, S. Hamacher and L. F. Scavarda, "Economic Assessment of Biodiesel Production from Waste Frying Oils," Bioresource Technology, Vol. 101, No. 12, 2010, pp. 4415-4422. doi:10.1016/j.biortech.2010.01.101

[8] L. Simasatitkul, R. Gani and A. Arpornwichanopa, "Optimal Design of Biodiesel Production Process from Waste Cooking Palm Oil," Procedia Engineering, Vol. 42, 2012, pp. 1292-1301.

[9] P. Chitra, P. Venkatachalam and A. Sampathrajan, "Optimisation of Experimental Conditions for Biodiesel Production from Alkali-CatalysedTransesterification of JatrophacurcusOil," Energy Sustainable Development, Vol. 9, No. 3, 2005, pp. 13-18. doi:10.1016/S0973-0826(08)60518-9

[10] S. Gryglewicz, "Rapeseed Oil Methyl Esters Preparation Using Heterogeneous Catalysts," Bioresource Technology, Vol. 70, No. 3, 1999, pp. 249-253.doi:10.1016/S0960-8524(99)00042-5

[11] S. Furuta, H. Matsuhashi and K. Arata, "Biodiesel Fuel Production with Solid Super Acid Catalysis in fixed Bed Reactor under Atmospheric Pressure," Catalyst Commu- nication, Vol. 5, No. 12, 2004, pp. 721-723. doi:10.1016/j.catcom.2004.09.001

[12] S. Hama, H. Yamaji, M. Kaieda, M. Oda, A. Kondo and H. Fukuda, "Effect of Fatty Acid Membrane Composition on Whole-Cell Biocatalysts for Biodiesel-Fuel Production," Biochemical Engineering Journal, Vol. 21, No. 2, 2004, pp. 155-160. doi:10.1016/j.bej.2004.05.009

[13] M. Oda, M. Kaieda, S. Hama, H. Yamaji, A. Kondo and E. Izumoto, "Facilitator Effect of Immobilized Lipase- Producing RhizopusoryzaeCells on Acyl Migration in Biodiesel-Fuel Production," Biochemical Engineering Journal, Vol. 23, No. 1, 2004, pp. 45-51. doi:10.1016/j.bej.2004.10.009

[14] W. Du, Y. Xu, D. Liu and J. Zeng, "Comparative Study on Lipase-Catalyzed Transformation of Soybean Oil for Biodiesel Production with Different Acyl Acceptors," Journal of Molecular Catalysis B: Enzymatic, Vol. 30, No. 3-4, 2004, pp. 125-129. doi:10.1016/j.molcatb.2004.04.004

[15] C. J. Shieh, H. F. Liao and C. C. Lee, "Optimization of Lipase-Catalyzed Biodiesel by Response Surface Meth- odology," Bioresource Technology, Vol. 88, No. 2, 2003, pp. 103-106. doi:10.1016/S0960-8524(02)00292-4

[16] Y. Chisti, "Biodiesel from Microalgae," Biotechnology Advances, Vol. 25, No. 3, 2007, pp. 294-306. doi:10.1016/j.biotechadv.2007.02.001

[17] H. I. El-Shimi, N. K. Attia, S. T. El-Sheltawy and G. I. El-Diwani, "Reactive Extraction of Microalgae for Biodiesel Production: an Optimization Study". The 30th International Conference on Solid Waste Technology and Management (ICSW 2015), Philadelphia, PA U.S.A., March 15-18, 2015.

[18] C. S. Jones and S. P. Mayfieldt, "Algae Biofuels: Versatility for the Future of Bioenergy," Current Opinion in Biotechnology, Vol. 23, No. 3, 2012, pp. 346-351. doi:10.1016/j.copbio.2011.10.013

[19] Gulab Chand Shah, AlkeshPatidar, VikashUrkude, Anil Hurmale, SudheeerChoudhary, MahavirYadav and ArchanaTiwari, "Analysis and Characterization of Algal Oil by Different Chromatographic Techniques for the High Production of Biodiesel from Scenedesmusdimorphus", International Journal of Environment and Bioenergy, Vol. 4, No. 1, pp. 22-35, 2012.

[20] H. I. El-Shimi, N. K. Attia, S. T. El-Sheltawy and G. I. El-Diwani, "Biodiesel Production from Spirulina-Platensis Microalgae by In-Situ Transesterification Process". Journal of Sustainable Bioenergy Systems (JSBS), Vol. 3, pp. 224-233, 2013

[21] GuanHua Huang, Feng Chen, Dong Wei, XueWu Zhang and Gu Chen, "Biodiesel production by microalgal biotechnology", Applied Energy, Vol. 87, pp. 38–46, 2010.

[22] FizzaNasir, AnsaJavaid, SabahatWaris, ToobaSaghir, Mehrin Bashir, SadafShahzadiTalib and SamiaMajeed, "A Review: ALGAE Used as Biofuel", International Journal of Water Resources and Environmental Sciences, Vol. 1, No. 2, pp. 43-66, 2012.

[23] H. I. El-Shimi, N. K. Attia, A. A. Abd El-Aal, S. T. El-Sheltawy and G. I. El-Diwani, "Quality Profile of Spirulina-platensisOilgae Extraction for Biodiesel Production". Indian Journal of Applied Research (IJAR), Vol. 5, No. 3, pp. 16-21, 2015

[24] Xiaobo Fu, Dianhong Li, Jie Chen, Yuanming Zhang, Weiya Huang, Yi Zhu, Jun Yang and Chengwu Zhang, " A microalgae residue based carbon solid acid catalyst for biodiesel Production", Bioresource Technology, Vol. 146, pp. 767–770, 2013.

[25] R. Halim, M. K. Danquah and P. A. Webley, "Extraction of Oil from Microalgae for Biodiesel Production: A Re- view," Biotechnology Advances, Vol. 30, No. 3, pp. 709-732, 2012. doi:10.1016/j.biotechadv.2012.01.001

[26] J. Sheng, R. Vannela and B. E. Rittmann, "Evalution of Methods to Extract Andquantify Lipids from Synechocys- tis PCC 6803," Center for Environmental Biotechnology, The Biodesign Institute, Arizona University, Tucson, 2011.

[27] G. El-Diwani, N. K. Attia and S. I. Hawash, "Development and Evaluation of Biodiesel Fuel and Byproducts from Jatropha Oil," International Journal of Environ- mental Science and Technology, Vol. 6, No. 2, pp. 219-224, 2009.

[28] A.V. Bridgwater and G.V.C. Peacocke, "Fast pyrolysis processes for biomass", Renewable and Sustainable Energy Reviews, Vol. 4, pp. 1-73, 2000

[29] S.A. Hanafi, M.S. Elmelawy, H.A. El-Sayed and Nasser H. Shalaby, "Hydrocracking of Waste Cooking Oil as Renewable Fuel on NiW/SiO2-Al2O3 Catalyst", Journal of Advanced Catalysis Science and Technology, Vol. 2, pp. 27-37, 2015.

[30] Marian Elmoraghy and Ihab H. Farag, "Bio-jet Fuel from Microalgae: Reducing Water and Energy Requirements for Algae Growth", International Journal of Engineering and Science, Vol. 1, No. 2, pp. 22-30, 2012.

[31] Pankaj Kumar, M.R. Suseela and KiranToppo, " Physico-Chemical Characterization of Algal oil: a Potential Biofuel", Asian J. Exp. Biol. Sci., Vol. 2, No. 3, pp. 493-497, 2011.

[32] M. J. Haas, K. M. Scott, W. N. Marmer and T. A. Foglia, "In Situ Alkaline Transesterification: An Effective Method for the Production of Fatty Acid Esters from Vegetable Oils," Journal of the American Oil Chemist's Society, Vol. 81, No. 1, pp. 83-89, 2004. doi:10.1007/s11746-004-0861-3

[33] G. Hincapié, F. Mondragón and D. López, "Conventional and in Situ Transesterification of Castor Seed Oil for Bio- diesel Production", Fuel, Vol. 90, No. 4, pp. 1618- 1623, 2011. doi:10.1016/j.fuel.2011.01.027

[34] K. J. Harrington and C. D'Arcy-Evans, "A Comparison of Conventional and in Situ Methods of Transesteri- fication of Seed Oil from a Series of Sunflower Cultivars," Journal of the American Oil Chemists' Society, Vol. 62, No. 6, pp. 1009-1013, 1985. doi:10.1007/BF02935703

[35] Tatiana Rodrigues da Silva Baumgartner, Jorge Augusto Mendes Burak, Dirceu Baumgartner, Gisella Maria Zanin and Pedro Augusto Arroyo (2013), "Biomass Production and Ester Synthesis by In Situ Transesterification/Esterification Using the Microalgae Spirulinaplatensis", International Journal of Chemical Engineering, Vol. Article ID 425604, 7 pages, 2013. Retrieved from http://dx.doi.org/10.1155/2013/425604

[36] E.A. Ehimen, Z. F. Sun and C. G. Carrington, "Variables Affecting the in Situ Transesterification of Microalgae Lipids," El-Sevier Fuel, Vol. 89, No. 3, pp. 677- 684, 2010

[37] Bradley D. Wahlen, Robert M. Willis and Lance C. Seefeldt, "Biodiesel production by simultaneous extraction and conversion of total lipids from microalgae, cyanobacteria, and wild mixed-cultures", El-SevierBioresource Technology, Vol. 102, pp. 2724–2730, 2010

[38] S.B. Velasquez-Orta, J.G.M. Lee and A. Harvey, "Alkaline in situ transesterification of Chlorella vulgaris", El-Sevier Fuel, Vol. 94, pp. 544–550, 2012

[39] C. Silva, L.A. Fabiano, G. Cameron, and W. D. Seider, "Optimal Design of an Algae Oil Transesterification Process", Proceedings of the 11th International Symposium on Process Systems Engineering, Philadelphia, PA U.S.A., 15-19 July 2012.

[40] Lin Chen, Tianzhong Liu, Wei Zhang, Xiaolin Chen and Junfeng Wang, "Biodiesel production from algae oil high in free fatty acids by two-step catalytic conversion", El-Sevier Bioresource Technology, Vol. 111, pp. 208–214, 2012.

[41] Rangel, C. de O., "Influeencia da Luz e Ureeia no CrescimentoeConteuudo de Clorofila da Biomassa de Spirulina-platensis", M.Sc. Thesis, University of Sao Paulo, S. Paulo, Brasil, pp. 129, 2000.

[42] S.M. Hoseini, K. Khosravi-Darani and M.R. Mozafari, "Nutritional and Medical Applications of Spirulina Microalgae", Mini-Reviews in Medicinal Chemistry, Vol. 13, pp. 1231-1237, 2013

[43] Robert Bernard Levine, "The Production of Algal Biodiesel using Hydrothermal Carbonization and In-situ Transesterification", Ph.D. Thesis, Chem. Eng. Dept., University of Michigan, pp. 20-57, 2013.

[44] N. Zahroojian, H. Moravej, and M. Shivazad, "Effects of Dietary Marine Algae (Spirulinaplatensis) on Egg Quality and Production Performance of Laying Hens", J. Agr. Sci. Tech., Vol. 15, pp. 1353-1360, 2013

[45] HartmutGaese, "Chemical Composition and Potential Application of Spirulina-platensis Biomass", International Journal of Agr.&Env., Vol. 4, pp. 32-40, 2012.

[46] B. Brian He, "In-situ transesterification of Microalgal Oil to produce Algal Biodiesel", National Institute for Advanced Transportation Technology, University of Idaho, Final Report, KLK768, N12-10, pp. 7, 2012.

[47] Michele R. Andrade and Jorge A.V. Costa, "Mixotrophic cultivation of microalga Spirulinaplatensis using molasses as organic substrate", El-Sevier Aquaculture, Vol. 264, pp. 130–134, 2007.

[48] Mukesh Kumar and M.P. Sharma, "Production Methodology of Biodiesel from Microalgae", International Journal of Applied Engineering Research, Vol. 8, No. 15, pp. 1825-1832, 2013

[49] S. Nagarajan, S. K. Chou, S. Y. Cao, C. Wu and Z. Zhou, "An Updated Comprehensive Techno-Economic Analysis of Algae Biodiesel," Bioresource Technology, 2012

[50]SayedaM.Abdo, S.Z. Wahba, Gamila H. Ali, S.A. Abo El-Enin, K.M. El-Khatib, M.I. El-Galad and G.I. El Diwani, "Preliminary economic

assessment of biofuel production from microalgae", Renewable and Sustainable Energy Reviews, 2015.
[51] Max S. Peters and Klaus D. Timmerhaus, "Plant Design and Economics for Chemical Engineers", McGraw-Hill, Inc., New York, Fourth Edition, pp. 20-35, 1991
[52] A. M. Zaki, "Plant and Process Economics for Chemical Engineers:, B. Sc. Academic Course, Chem. Eng. Dept., Cairo University, 2010
[53] Y. Zhang, M. A. Dub, D. D. McLean and M. Kates, "Biodiesel Production from Waste Cooking Oil: Economic Assessment and Sensitivity Analysis", Bioresource Technology, Vol. 90, No. 3, pp. 229-240, 2003

AUTHOR BIOGRAPHY

H. I. El-Shimi; Researcher and Lecturer Associate at Chemical Engineering Department, Faculty of Engineering, Cairo University, Egypt.

N. K. Attia; Assistant Professor at Chemical Engineering and Pilot Plant Department, National Research Center (NRC), Egypt.

G. I. El-Diwani; Professor of Chemical Engineering at Chemical Engineering and Pilot Plant Department, National Research Center (NRC), Egypt.

S. T. El-Sheltawy; Professor of Inorganic Industries Technology at Chemical Engineering Department, Faculty of Engineering, Cairo University, Egypt.