VOL. 11, NO. 17, SEPTEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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EVALUATION OF BIODIESEL PRODUCTION FROM SPENT COOKING OILS: A TECHNO-ECONOMIC CASE STUDY OF EGYPT

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ABSTRACT

Biodiesel is one of the feasible alternatives to minimize the diesel shortage in Egypt and worldwide. It produced by transesterification of oils and fats in presence of homogenous or heterogeneous catalysts. Feedstock is the controlling factor of biodiesel industry. However, virgin vegetal oils are expensive to obtain biodiesel, so utilization of spent cooking oils (SCO) is considered a cheap alternative for biodiesel production. In this research, techno-economic appraisal was performed on the Egyptian biodiesel business using SCO as feedstock, and homogeneous (KOH) and heterogeneous (Phosphate rock, Na_2SiO_3 and CaO) catalysts. The economic analyses were then compared; to determine the most effective technique for biodiesel production. Also, sensitivity and break-even analyses were evaluated for all catalysts on the variations in SCO and biodiesel prices using simple rate of return (SRR). PR is recommended to be the ideal catalyst for biodiesel industry according to the current situation in Egypt.

Keywords: biodiesel, transesterification, techno-economic appraisal, sensitivity and break-even analyses, simple rate of return.

INTRODUCTION

Diesel fuel shortage, hiking of crude oil prices and the greenhouse gases emissions of fossil fuels incentive the Egyptian researchers to search and develop for bio-energy sources [1, 2]. Currently, the annual worldwide consumption of petroleum-based fuels is approximately 1,062 million tons, and it is expected to rise to an estimated 2,053 million tons in 2030 [3]. Biodiesel is a renewable, biodegradable, non-toxic and green substitute fuel along petrol-diesel to create blends [4]. It reduces the level of air toxics emission by approximately 80% more than fossil fuels [5, 6].

Biodiesel is available now but, non-commercial. Feedstock cost is the bottleneck of biodiesel marketing on industrial scale; as it represents more than 90% of biodiesel manufacturing cost [7, 8]. Additionally, food crisis versus diesel fuel debate will rose if edible virgin oils (e.g. cotton, soybean, sunflower, etc.) were investigated for biodiesel production. Thus, utilization of waste oils from cooking/frying processare concerned for biodiesel industry development, as it will offer a triple facet solution: environmental, economic and waste control [9].

Technically, it produced from oils (edible or non-edible) and fats by transesterification process using homogeneous [10-12] or heterogeneous catalysts [9, 13-15] with more than 94% yield [16]. It is estimated that two million tons of edible oils are consumed in Arab Republic of Egypt each year; hence huge amounts of spent cooking oils (SCOs) are generated. The data suggests around 30% of SCOs can be collected for biodiesel industry instead of discharging into the sewage system and generating environmental problems [17]. Furthermore, Egypt consumes approximately 37 thousand tons of diesel fuel per day, in which 50-60% of this amount is importedby US$800-1100/ton according to the statistics report directed by EIA (U.S. Energy Information Administration). In this report, economic analyses of the biodiesel production from SCO are performed using different catalysts viable for the Egyptian current situation.

2. PROCESS DESIGN AND CASE STUDY

2.1. Background of the case study

Egypt is a great country with a total area of 1 million km^2 and total population of 93 million people according to the Central Agency for Public Mobilization and Statistics of Egypt. In 2005 Egypt's diesel demand was 10.7 million tons, and increased to 13.32 million tons in 2015 based on EIA statistics. The diesel price had been increasing from October 2008 to July 2014by 64%, and now its price equals EGP 1.85/liter (~US$ 238/metric ton). There is no policy in Egypt to use at least 1% biodiesel as a blend in fossil diesel, but the Egyptian Government must encourage the marketing of biodiesel business by raise the people awareness, offering tax incentives and subsidies (e.g. project land and water) on biofuel as it has been applied to natural gas. Due to the diesel shortage, a biodiesel factory with an annual capacity of 600 kilotons will reduce the diesel imports by approximately 9%, and save at least $300/ton according to the selling price of biodiesel, $500/ton. Therefore, this paper focuses on the techno-economic appraisal of the "biodiesel industry" based on 600 kilotons of feedstock.

2.2. Biodiesel production process using homogeneous catalysts

First of all, the collected feedstock (SCO) is filtered; to remove the suspended burned-food bits, and dried at 110°C for 2h; to evaporate the unwanted moisture content. For biodiesel production using a base catalyst (KOH), the SCO is pretreated with the sulphuric acid, H_2SO_4 (esterification) and methanol; to esterify the FFA to fatty acid methyl esters (FAMEs) or biodiesel, and hence avoiding soap formation during biodiesel manufacturing [18,19]. After pretreatment process, the by-product water

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is decanted from the treated SCO, and thenexcess CH_3OH is reacted with KOH to produce methoxide, CH_3OK which catalyze the biodiesel production process. Transesterification reaction is achieved between the treated SCO and methyl alcohol over potassium methoxide. Subsequently, the products mixture is fed into a decanter; to separate the crude biodiesel from glycerol layer. The crude FAMEs stream is distilled under vacuum; to evaporate the residual alcohol, and then washed with hot water (55°C) for 3 times in extraction columns; to absorb the residual catalyst and glycerol. The water layer is decanted, and the biodiesel is dried at 110°C before storing. On the other hand, the glycerol layer is neutralized by H_2SO_4 [20]; to get rid of all the remaining substances such as FFA, methanol, and KOH. Neutralization process generates three layers: FFA in the top; which is recycled to esterification reactor, glycerol in the middle layer, and potassium sulphate (K_2SO_4) in the bottom, which is dried and used as fertilizer. After neutralization, the glycerol is washed by water (55°C) for at least three times, then decanted and dried under at 110°C. The pure glycerin is stored in a tank. Biodiesel production processes using H_2SO_4 followed by KOH are shown in Figure-1.

2.3. Biodiesel production process using heterogeneous catalysts

Heterogeneous catalysts such as calcium oxide [13, 14, 21], phosphate rock [9, 22] and sodium metasilicate [15, 23-25] are extensively used as an alternative to homogeneous catalysts. Biodiesel manufacturing using solid catalysts involved fewer unit operations compared to KOH and H_2SO_4 catalyzed processes [26, 27]. The SCO is firstly filtered and heated to the specified temperature (e.g. 65°C), and then reacts with the alcohol in presence of solid catalyst. At the process end, the catalyst was removed through settlers or hydrocyclones; to use in the next batch. The products mixture is distilled under vacuum; to recover the excess methanol, and then transferred into a decanter; to get two distinct layers of biodiesel and glycerol; due to the densities difference of 0.86 and 1.22 g/ml, respectively. The glycerol (99% purity) is stored, while the FAMEs are treated with hot water (55°C) for 2 times; to get rid of alcohol, catalyst and glycerol traces. The water layer is then decanted; to purify the biodiesel before storing, as shown in Figure-2. These processes are applied to the phosphate rock (PR) or any solid powder, but in case of sodium metasilicate (Na_2SiO_3), crushing and grinding operations must be achieved; as it supplied in rocks form. Calcium oxide (CaO) is produced by the calcination of grinded limestone ($CaCO_3$) at 800°C in a rotary kiln.

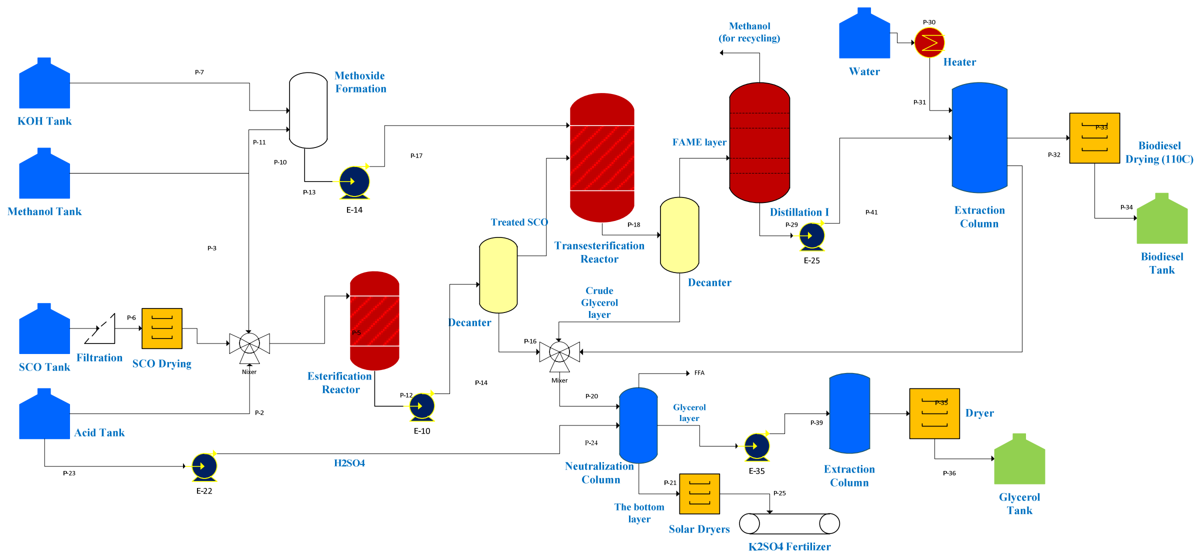

Figure-1. Biodiesel production process using homogeneous catalysts.

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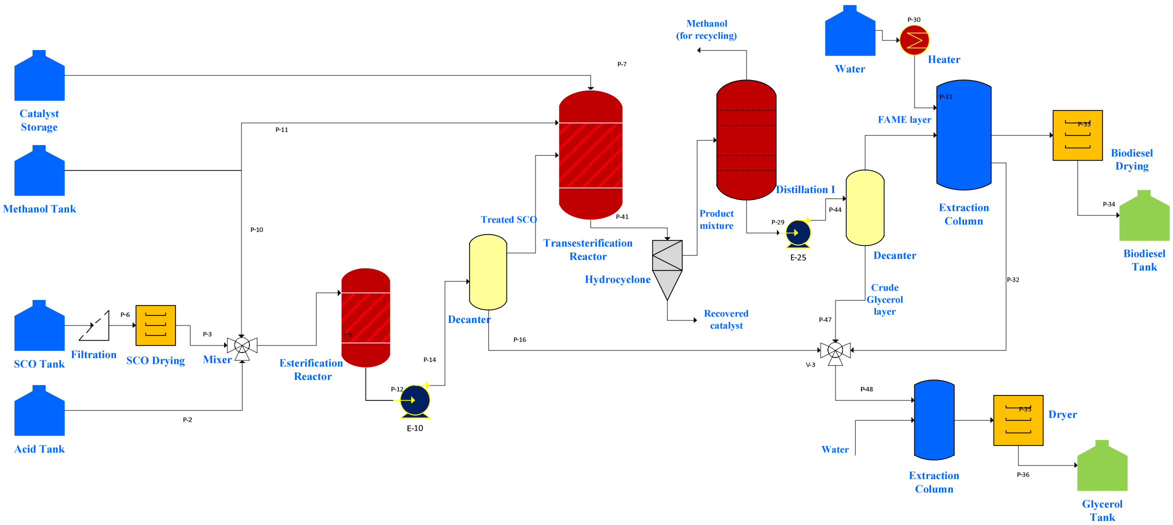

Figure-2. Biodiesel production process using heterogeneous catalysts.

3. RESULTS AND DISCUSSIONS

3.1. Process results

Homogeneous catalysts; H_2SO_4 followed by KOH and heterogeneous; phosphate rock [$Ca_3(PO_4)_2F$], sodium metasilicate (Na_2SiO_3) and calcium oxide (CaO) are investigated in this study; since phosphate rock is abundant in different areas in Egypt such as El Sebaeya' Mine (North of Aswan City-El Nile Valley) and Abu Tartour'Mine (Red Sea region), and sodium silicate is available by many Egyptians manufacturers such as Silica Egypt Company and the Egyptian Saudi Company for Modern Chemicals, while CaO is produced by limestone calcination at high temperatures (e.g. 650-900^{o}C), where limestone is cheap raw material and mined from Tourah-Helwan. In general, spent cooking oil (SCO) contains free fatty acids (FFA) in range of 2-7% as it is subjected to cooking/frying temperatures from 120^{o}C to 180^{o}C in houses and restaurants [28]. The average fatty acids composition is 7.2% Palmetic acid (C16:0), 3.67% stearic acid (C18:0), 29.6% Oleic acid (C18:1) and 60% Linoleic acid (C18:2), while the average molecular weight is approximately 916. The transesterification conditions for all catalysts are kept in optimum levels (Table-1); to produce 600,000 tons of biodiesel.

Table-1. Optimum operating conditions using both homogeneous and heterogeneous catalysts.

Components	Catalyst			
	Potassium hydroxide (KOH)	**Phosphate Rock** (PR)	**Sodium metasilicate** (Na_2SiO_3)	**Lime** (CaO)
Reaction time (h)	1.17	0.5	1	3
Reaction temperature (^{o}C)	53	55	60	65
Alcohol:oil molar ratio (x:1)	7.5	3	7.5	12
Catalyst loading (%wt/wt oil)	1	7	3	8
Pressure (atm)	1	1	1	1
Stirring rate (rpm)	266	300	250	300
Biodiesel conversion (%)	99	99.6	99.7	95
Recyclability (times)	1	1	6	1
Reference No.	[10]	[9]	[23]	[13]

3.2. Economic assessment

Several assumptions were done for the evaluation of biodiesel industry; since raw material cost, biodiesel and glycerol selling prices are estimated in accordance with the Egyptian market prices. The SCO will supply in polyethylene teraphethalate (PET) bottles, hence they will increase the industry revenues. Also, the recovered catalyst will marketed; PR as a fertilizer feedstock, while Na_2SiO_3 will recycle to its factory by \$50/ton lower than its purchased cost, and no income is detected for CaO. The process results for all recommended catalysts are summarized in Table-2. The total equipment cost (TEC) is calculated for each individual catalyst and illustrated in Table-3 [29].

In Table-3, 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 (US$) of each specific equipment used in the processing were determined. It is assumed that the working days of biodiesel plant are 300 per year for 3 shifts per day.

The total capital investment (TCI) and specific investment cost (SIC) for each biodiesel process catalyzed by different catalysts are estimated in Table-4. The total capital investment (TCI) is the sum of fixed capital investment (FCI) and working capital investment (WCI), and FCI is the sum of physical plant cost (PPC) and indirect plant cost (IPC). WCI is assumed to be 15% of TCI; as the process generates just two products (biodiesel and glycerol), whose are already marketed, while the specific investment cost (SIC) is the TCI divided by the annual biodiesel production capacity, and all costs are calculated with respect to the TEC. Various categories are involved in calculating the TCI [29,30].

The total production cost of biodiesel industry in Egypt for different viable catalysts is determined and illustrated in Table-5. In general, the raw material and utilities (Electrical distribution, air instrument and steam generation systems) contribute around 70-75% of total costs [31], while for biodiesel production using lipase as a catalyst, it contributed for 85% of total costs [28]. In this research, the feedstock represents only 83% of all costs, and the cost analysis for each category of biodiesel production cost (BPC) from SCO using PR as a catalyst is shown in Figure 3. If virgin vegetable oil is suggested as a feedstock for biodiesel industry, it will contribute for more than 95% of BPC [32]; therefore utilization of SCO is more economical feedstock.

Table-2. Process results for different catalyst types.

Item	**Unit cost** (US$/t)	**Quantity** (t/yr)				**Price** (US$/yr)			
		KOH	**PR**	**Na_2SiO_3**	**CaO**	**KOH**	**PR**	**Na_2SiO_3**	**CaO**
Raw materials									
Feedstock (SCO)	380	600000	600000	600000	600000	228000000	228000000	228000000	228000000
Methyl alcohol	1200	16941	6777	16941	27106	20329412	8131765	20329412	32527059
Catalyst	*	6000	42000	18000	48000	102000	2100000	4500000	3024000
H_2SO_4	1400	6000	6000	0	6000	8400000	8400000	0	8400000
						256831412	246631765	252829412	271951059
Products									
Biodiesel	500	594000	597600	598200	570000	297000000	298800000	299100000	285000000
Crude glycerin	250	59400	59760	59820	57000	14850000	14940000	14955000	14250000
Recycled catalyst (90%)	**	0	37800	16200	43200	0	945000	3240000	0
K_2SO_4 Fertilizer	25	1440	0	0	0	36000	0	0	0
PET bottles	350	6000	6000	6000	6000	2100000	2100000	2100000	2100000
Annual revenues						313986000	316785000	319395000	301350000
	Unit cost (US$/t)								
Category	KOH	PR	Na_2SiO_3	CaO					
*Catalyst	17	50	250	63					
**Recycled catalyst	0	25	200	0					

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Table-3. Total equipment costs (TEC) for different catalyst types.

Equipment	**Units No.**				**Unit cost** (US$)	**Total cost** (US$)			
	KOH	**PR**	**Na_2SiO_3**	**CaO**		**KOH**	**PR**	**Na_2SiO_3**	**CaO**
Oil storage tanks (100 m^3)	22	22	22	22	25000	550000	550000	550000	550000
Methanol storage tanks (100 m^3)	7	3	7	10	25000	175000	75000	175000	250000
H_2SO_4 storage tanks (100 m^3)	1	1	0	1	25000	25000	25000	0	25000
Calcination furances (Shaft furance or rotary kiln 1 million Btu/hr)	0	0	1	1	500000	0	0	500000	500000
Crushers (Jaw or impact crusher, 6ton/hr capacity, 20kW)	0	0	0	1	50000	0	0	0	50000
Grinders (Ball or vertical roll mills, 10ton/hr capacity, 46kW)	0	0	0	1	300000	0	0	0	300000
Esterification reactors (Jacketed & Agitated 30 m^3)	5	5	0	6	113000	565000	565000	0	678000
Transesterification reactors (Jacketed & Agitated 30 m^3)	5	5	6	6	113000	565000	565000	678000	678000
Filters (Hydrocyclone, 1m diameter, 25-50 m^3/h)	0	4	4	4	50000	0	200000	200000	200000
Splitters/Mixers (Propeller, 10 hp)	10	10	5	10	10200	102000	102000	51000	102000
Decanters/Centrifuges (bottom driven 3m diameter)	5	5	6	6	37000	185000	185000	222000	222000
Pumps (progressive cavity type, 30gallon/min)	20	20	16	20	11000	220000	220000	176000	220000
Extraction columns/Distillation Towers (2m Diameter,15m Height)	9	7	7	8	500000	4500000	3500000	3500000	4000000
Biodiesel storage tanks (100 m^3)	22	22	22	21	25000	550000	550000	550000	525000
Glycerol storage tanks (100 m^3)	2	2	2	2	25000	50000	50000	50000	50000
					TEC	7487000	6587000	6652000	8350000

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Table-4. Total capital investments (TCI) for different catalyst types.

Capital investment category	% of TEC	Cost US$			
		KOH	**PR**	**Na_2SiO_3**	**CaO**
Total equipment cost (TEC)	100	7487000	6587000	6652000	8350000
Equipment delivery cost	10	748700	658700	665200	835000
Installation cost	20	1497400	1317400	1330400	1670000
Piping	20	1497400	1317400	1330400	1670000
Buildings	10	748700	658700	665200	835000
Utilities	15	1123050	988050	997800	1252500
Instrumentation and Control	15	1123050	988050	997800	1252500
Site Development	10	748700	658700	665200	835000
Auxiliary buildings	5	374350	329350	332600	417500
	PPC	15348350	13503350	13636600	17117500
	% of PPC				
Design and Eng.	20	3069670	2700670	2727320	3423500
Contractor' fee	20	3069670	2700670	2727320	3423500
Contingency	10	1534835	1350335	1363660	1711750
Legal expenses	10	1534835	1350335	1363660	1711750
	IPC	9209010	8102010	8181960	10270500
	FCI	24557360	21605360	21818560	27388000
	WCI	15%TCI	15%TCI	15%TCI	15%TCI
	TCI	29468832	25926432	26182272	32865600
	SIC	49.61	43.38	43.77	57.66

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Table-5. Biodiesel production cost (BPC) for different catalyst types.

Biodiesel production cost	Unit cost (US$)	Cost (US$)			
		KOH	PR	Na_2SiO_3	CaO
Variable Cost					
Raw Materials	\$0.43 (KOH), \$0.41 (PR), \$0.42 (Na_2SiO_3), \$0.45 (CaO)/L SCO	256831411.8	246631764.7	252829411.8	271951058.8
Miscellaneous materials	10% M&O	74870	65870	66520	83500
Electricity	\$0.1/kWh	4158000	5976000	7477500	7980000
Shipping & Packaging	Assuming zero; as it supplied by customers	0	0	0	0
Fixed Cost					
Maintenance and operational cost (M&O)	10%TEC	748700	658700	665200	835000
Operating labor	\$13500/employee/year	1540000	1680000	1680000	1820000
Depreciation	Striaght-line depreciation over 15 years factory life	449220	395220	399120	501000
Plant overheads	50% of labor and M &O	1144350	1169350	1172600	1327500
Interest	2% TEC	149740	131740	133040	167000
Property insurance cost	5% TEC	374350	329350	332600	417500
Rent	Plant land will be free	0	0	0	0
Royalities	No appreciated	0	0	0	0
	DPC	265470641.8	257037994.7	264755991.8	285082558.8
General expenses	25% of labor and M&O	572175	584675	586300	663750
Contingency	10% of labor, M&O and plant overheads costs	343305	350805	351780	398250
	IPC	915480	935480	938080	1062000
	TPC	266386121.8	257973474.7	265694071.8	286144558.8
	BPC/ton	448.5	431.7	444.1	502.1

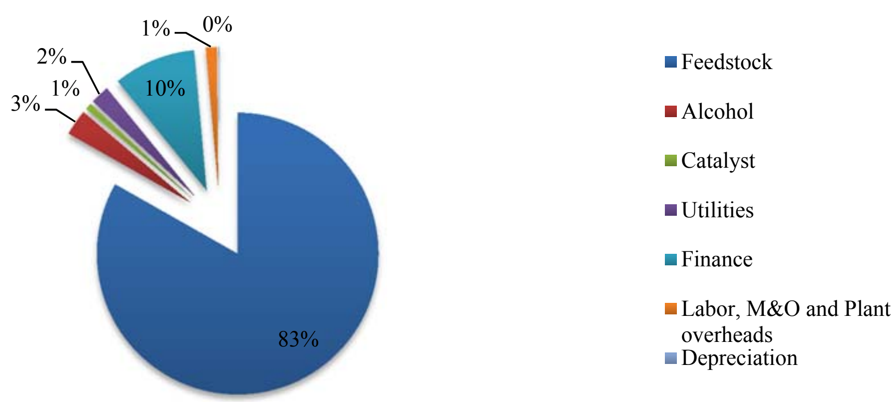

Figure-3. Cost analysis of biodiesel industry in Egypt.

To evaluate the biodiesel project, some of economic indicators should be estimated such as the net profit "Equation (1)", simple rate of return (SRR) and payback period. For a new investment, the minimum SRR in an established market is 15-20%, and the maximum pay-back period is 5 years [28, 30]. The Egyptian

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Government offering tax incentives for the new industries up to 10 years. The economic indicators for biodiesel production using different catalysts are illustrated in Table 6, based on the feedstock capacity of 600 kilotons/year.

$$\text{Net profit} = \text{Total revenues - TPC} \quad (1)$$

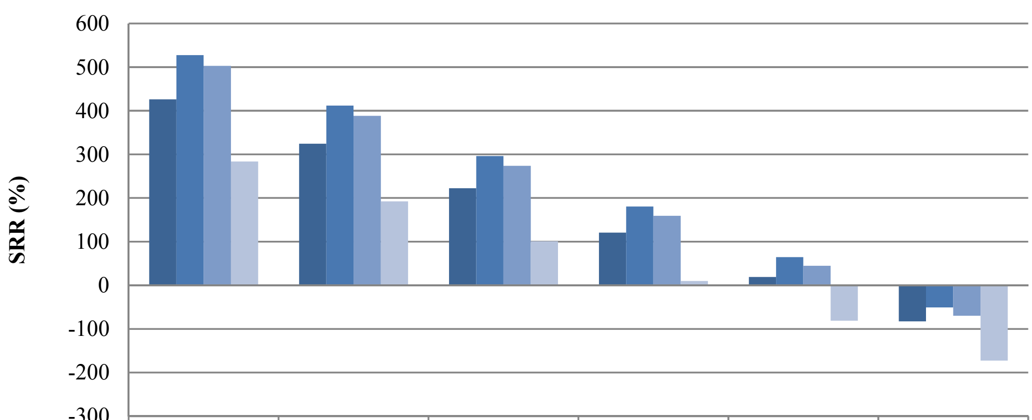
Table-6. Economic indicators of biodiesel industry according to catalyst type.

Economic indicator	Catalyst type			
	KOH	**PR**	**Na_2SiO_3**	**CaO**
Net profit (US$)	47,599,878	58,811,525	53,700,928	15,205,441
%SRR	161.5	226.8	205.1	46.3
Pay-back period, year	0.51	0.37	0.40	1.74

3.3. Sensitivity analysis

The controlling factor of biodiesel industry is the feedstock (SCO) prices, so in the sensitivity analysis, the SCO cost and biodiesel price are varied to determine the sustainability of biodiesel business with the simple rate of return (SRR). The first year is the capital investments and the production has only 50% of the full capacity, while the 2nd year onwards rose to 100% of total production capacity. There are no taxes on the biodiesel factory for the first ten years according to the Egyptian policies and annual increase of 10% of manufacturing costs and biodiesel selling price is suggested. Assuming the biodiesel price is US$500/ton for the variations in SCO cost, while the reference SCO cost is suggested to be US$380/ton in Arab Republic of Egypt for biofuel price changes. Sensitivity analysis results are shown in Figure4and Figure-5.

Phosphate rock (PR) seems to be the most profitable catalyst for the biodiesel production in Egypt; where the acceptable SCO price is below $0.46/liter with SRR of approximately 60%, and the acceptable biodiesel price is above $0.41/liter as shown in Figure-4 and Figure-5. Sodium metasilicate has similar results to PR. On the other side, the acceptable SCO price for the homogeneous catalyst (KOH) is below $0.47/liter, while the transesterification process catalyzed by CaO have feasible SCO cost below $0.38/liter, and biodiesel selling price above $0.49. Sensitivity analysis indicated that biodiesel industry in Egypt can be implemented using homogeneous (KOH) or heterogeneous (PR or Na_2SiO_3) catalyst, and can be adapt with the variation in SCO costs and biofuel prices. However, PR is the most effective catalyst if all economic indicators (Table 6) and products quality are considered.



	0.25	0.3	0.35	0.4	0.45	0.5
KOH	426.2126108	324.4101369	222.607663	120.8051891	19.00271526	-82.79975862
PR	527.691297	411.97927	296.267243	180.555216	64.84318897	-50.86883805
Na2SiO3	503.0156597	388.4343125	273.8529652	159.271618	44.69027071	-69.89107654
CaO	283.5957389	192.314886	101.0340331	9.753180153	-81.52767277	-172.8085257

SCO prices (US$/L)

Figure-4. SRR sensitivity analysis with variation in SCO costs.

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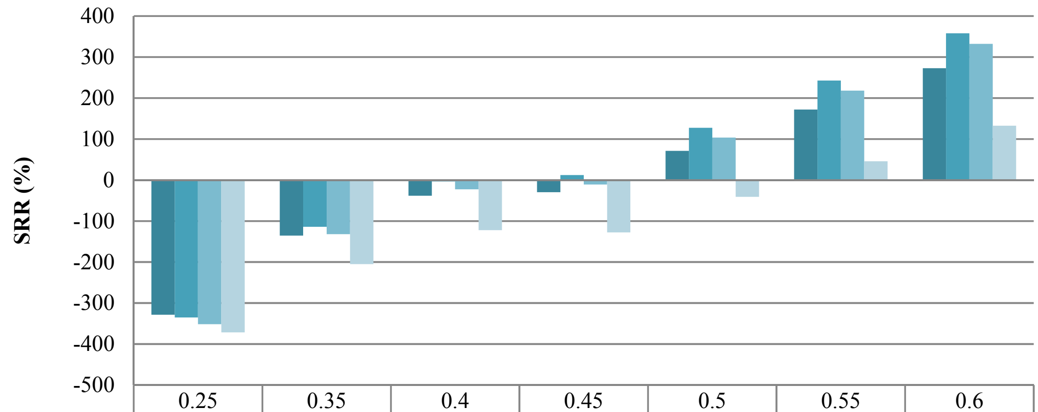

	0.25	0.35	0.4	0.45	0.5	0.55	0.6
KOH	-328.700224	-135.194082	-38.4410108	-29.6541578	71.13029135	171.9147405	272.6991896
PR	-335.429633	-114.15121	-3.51199779	12.08873563	127.3379145	242.5870934	357.8362724
Na2SiO3	-351.440505	-132.104307	-22.4362076	-10.612062	103.6255412	217.8631444	332.1007476
CaO	-371.825789	-205.329513	-122.081375	-127.516354	-40.7995433	45.91726697	132.6340773

Figure-5. SRR sensitivity analysis with variation in biodiesel prices.

3.4. 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 utilization of spent cooking oils in green fuel manufacturing. The break-even calculations reported that the minimum biodiesel price per ton is \$419.8, \$401.6, \$409.8and \$473.3 for KOH, PR, $Na_2SiO_3$and CaO respectively, based on the SCO cost of \$380 per ton. It is well-known that the crude oil prices are continuously varied; as in 2010 year, the Brent Crude Oil Spot price was \$77/barrel, and rose to \$120/barrel in 2012 then declined to \$36/barrel in December 2015. Over the year of 2015, the standard price per barrel was \$55 in January, \$60 in March, and \$46 in July and now its cost is about \$36 according to EIA statistics. Consequently, the standard diesel prices are changed. The 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 reported in Figure-6. As illustrated, the biodiesel and petro-diesel prices are matched when the Brent Crude Oil Spot cost is US\$55/barrel, therefore the biodiesel project is viable and feasible if the barrel standard petroleum price is above US\$55.

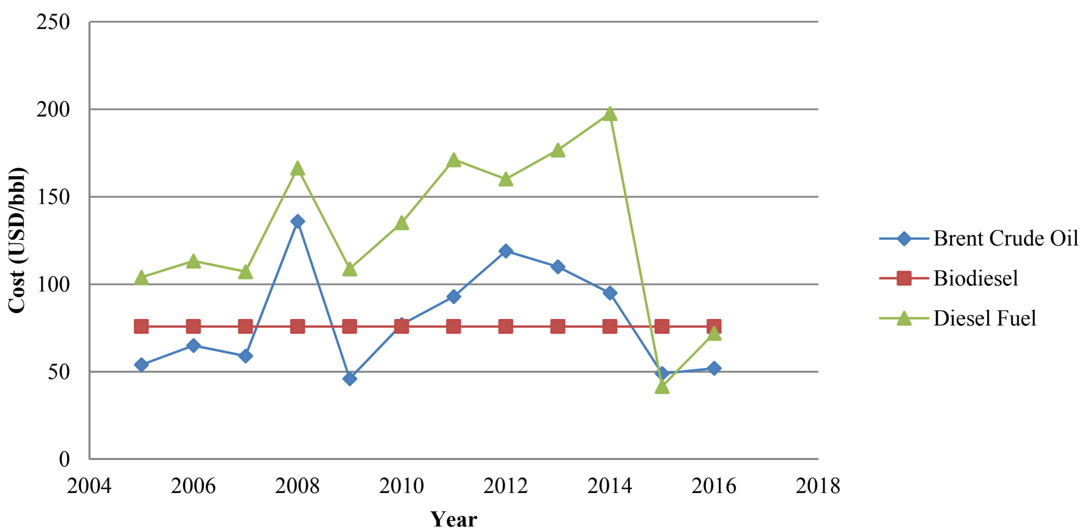

Figure-6. Break-even oil barrel chart.

4. CONCLUSIONS

In the recent research, Egyptian biodiesel industry from SCO is evaluated. Currently, the biodiesel business is not viable; because of the decline of Brent Crude Oil and diesel prices to \$36/barrel and \$0.26/L, respectively in Dec. 2015, but it is more profitable to export; as the average biodiesel price in Europe is \$1.01/L. KOH, PR and Na_2SiO_3 are acceptable catalysts for biodiesel manufacturing in Egypt based on the SCO cost of \$0.38/L and biodiesel selling price of \$0.5/L, and withstand the variations in the feedstock and biofuel prices, however PR is the perfect catalyst if all economic indicators are regarded. On the other hand, CaO is less beneficial and more expensive.

ACKNOWLEDGEMENTS

The authors are grateful to Faculty of Engineering, Cairo University (CUFE), and National Research Center (NRC), Arab Republic of Egypt, for the financial and technical support.

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