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Economic Evaluation of a Supercritical Methanol Process

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ABSTRACT

This paper presents the economic evaluation of a production of methyl esters (biodiesel) from Jatropha Curcas Oil (JCO) via a supercritical methanol process with glycerol as a by-product. A biodiesel production of 40000 tonnes-yr^{-1} via single step process is taken as case study. The biodiesel can be sold at USD 0.78 kg^{-1}, while the manufacturing and capital investment costs are in the range of USD 25.39million-year^{-1} and USD 9.41 millionyear^{-1},respectively. This study proved that biodiesel from JCO is the least expensive comparable to those found in other studies. It is also showed that biodiesel production via SM adding propane comparable and very attractive.

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INTRODUCTION

A lot of research has been done to produce biodiesel by using conventional process. However, no studies were found concerning the modelling and economic aspects of Jatropha Curcas Oil (JCO) as a feedstock generally and particularly JCO is converted to methyl esters (biodiesel) via supercritical transesterification with methanol and glycerol is obtained as a by-product. Besides, the main advantages of using supercritical transesterification with methanol compared to a conventional process include the following: (i) no catalyst is required; (ii) the process is not sensitive to either water or free fatty acid; and (iii) the free fatty acids in the oil are esterified simultaneously (Kasteren, J.M.N., Nisworo A. P., 2007). For this reason, this paper examines the economic aspects of a biodiesel plant using Jatropha curcas oil via supercritical process.

MATERIAL AND METHODS

In this study, the biodiesel production via supercritical methanol process consists of transesterification unit, methanol recovery, glycerol separation and biodiesel purification. The process units involved are plug folw reactor (PFR), flash evaporator (FT), distillation column (DC1 and DC2) and decanter (DEC). Fig. 1 shows the schematic diagram of SM process via single step developed for this study. The PFR involves in producing biodiesel from JCO and methanol. FT and DC1 used to recovered the excess methanol then recycled and mixed with the fresh methanol. After methanol recovery unit, the bottom

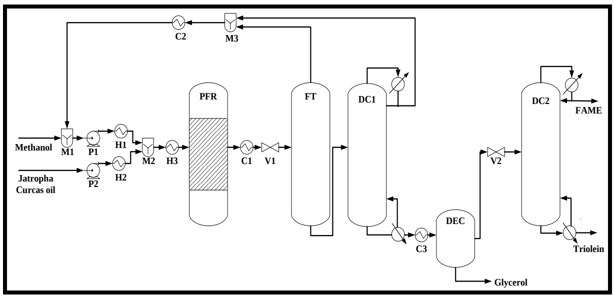

Fig. 1: Schematic diagram of SM process via single step.

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stream of DC1 is fed to a DEC to further separate glycerol-rich phase and biodiesel-rich phase. Finally biodiesel is obtained at distillate of DC2 with purity 99.96% and passes the European biodiesel standard EN 14214.

Table 1 gives the design parameters for the process units and utilities calculated based on the short cut design method (Yusuf, N.N.A.N., in press). The cost estimation was based on economic modelling, as shown in Table 2. All cost figures will be in 2011 USD. Table 3 show the prices of the raw materials, products, and utilities. In general, Daud W.R.W., 2002, claims that the equipment purchasing cost changes with time due to inflation:

$$C_{P_2} = C_{P_1}\left(\frac{I_2}{I_1}\right) \tag{1}$$

with C_{P_2} as the equipment purchasing cost at time 2, C_{P_1} as the equipment purchasing cost at time 1, and I_n as the cost index at time n. The cost index in this study will follow the Chemical Engineering Plant Cost Index (CEPCI).

The equipment purchasing cost also depends on size and is generally calculated as:

$$C_{P_2} = C_{P_1}\left(\frac{S_2}{S_1}\right)^{\alpha_n} \tag{2}$$

where C_{P_2} is the equipment for equipment 2, C_{P_1} is the equipment for equipment 1, S_2 is the size for equipment 2, S_1 is the size for equipment 1, and α_n is the cost index.

The fixed capital for equipment cost or inside battery limit (ISBL) is the cost for processing units, i.e., the reactors, mixers, heat exchangers, and pumps, among

Table 1: Design parameters.

Name	Number of units	Parameter
PFR	1	L= 0.8 m, D= 3.31 m, τ = 10 min, Orientation = Horizontal, MOC = 316SS
FT	1	L= 2.99 m, D= 1.02 m, τ = 10 min, Orientation = Vertical, MOC = CS
DC1	1	L= 5.55 m, D= 0.76 m, Packing Material = 1 in. Pall rings, MOC = CS, $N_{actual\ stages}$ = 7
DEC	1	L= 6.12 m, D= 1.58 m, τ = 60 min, Orientation = Horizontal, MOC = CS
DC2	1	L= 9.36 m, D= 2.30 m, Type of trays = Valve, MOC = CS, $N_{actual\ stages}$ = 12
H1	1	A= 15.95 m^2, Duty= 551.4 kW, MOC= 316SS, Type= Float head
H2	1	A= 13.16 m^2, Duty= 625.1 kW, MOC= 316SS, Type= Float head
H3	1	A= 10.48 m^2, Duty= 358.7 kW, MOC= 316SS, Type= Float head
C1	1	A= 21.41 m^2, Duty= 1374.6 kW, MOC= 316SS, Type= Float head
C2	1	A= 43.91 m^2, Duty= 296.9 kW, MOC= CS, Type= Fixed head
C3	1	A= 20.37 m^2, Duty= 356.1 kW, MOC= CS, Type= Float head
P1	1	Type= Centrifugal, η= 0.75, MOC= 316SS, Diver power= 68.1 kW
P2	1	Type= Centrifugal, η= 0.75, MOC= 316SS, Diver power= 65.1 kW

others. This cost was calculated by multiplying the total purchased equipment cost by a factor of 5, so that

$$ISBL = C_{p2} \text{ x } 5 \tag{3}$$

This factor is in agreement with the 4.7 Lang factor for fluids processing (Biegler, T.L, 1997). The cost calculation method also includes the outside battery limit (OSBL), which covers tankage, yards, roads, and other general facilities. The normal default value is 20% of ISBL. The fixed capital cost C_{FC} is

$$C_{FC} = ISBL + OSBL \tag{4}$$

$$C_{TCI} = C_{FC} + C_{WC} + C_{SC} \tag{5}$$

with total capital investment, C_{TCI}, start-up cost, C_{SC} and working capital, C_{WC}. Working capital is the funds required for routine operation, including inventories, accounts receivable and payable, and cash on hand.

$$C_{TP} = C_{DM} + C_{IM} + C_{GA} \tag{6}$$

with total production cost, C_{TP}, direct manufacturing cost, C_{DM}, indirect manufacturing cost, CIM and general and administrative cost, C_{GA}.

Table 2: Economic models for unit and utilities of SCM process (Biegler, T.L , 1997, Douglas, J.M., 1988).

Comp.	Cost (USD)	α, β	Base cost, C_0 (10^3) (USD)
PFR	$C_{PFR}= C_0(H/H_0)^{\alpha}(D/D_0)^{\beta}$, H=height column, D=diameter of column	0.81, 1.05	1
FT	$C_{DC1}=C_0(H/H_0)^{\alpha}(D/D_0)^{\beta}$ H=height column, D=diameter of column	0.81, 1.05	1
DC1	$C_{DC1}=C_0(H/H_0)^{\alpha}(D/D_0)^{\beta}$ H=height column, D=diameter of column	0.81, 1.05	1
DEC	$C_{DEC}=C_0(H/H_0)^{\alpha}(D/D_0)^{\beta}$ H=height column, D=diameter of column	0.78, 0.98	0.69
DC2	$C_{DC2}=C_0(H/H_0)^{\alpha}(D/D_0)^{\beta}$ H=height column, D=diameter of column	0.81, 1.05	1
Pump	$C_{pump}=C_0(P/P_0)^{\alpha}$, P=output power	0.39	1.5
Heat exchanger	$C_{HE}=C_0(A/A_0)^{\alpha}$, A=surface area	0.65	5

Table 3: The prices of raw material, products , and utilities used in this study.

Item	Specification	Price ($/tonne)	Ref.
Chemicals			
Methanol	-	268.71	(Lee, S., 2001)
Non-edible oil	Jatropha Curcas oil	330.21	(Abigail, M.,2012)
Glycerol	Pharmaceutical grade	1322.77	(Lee, S., 2001)
Biodiesel (B100)	Qualified to meet EN 14214 and ASTM D 6751	990	(Lee, S., 2001)
Utility			
Cooling water		0.013	(Seider, W.D.,2004)
Circulating heating oil		0.4	(Seider, W.D.,2004)
Medium- pressure steam (1135 kPa)		13.71	(Turton, R., 2012)
High-pressure steam (4201 kPa)		16.64	(Turton, R., 2012)
Electricity		0.062 kWh^{-1}	(Zhang, Y.,2003)

RESULT AND DISCUSSION

Table 4 gives the result of the biodiesel cost for the SCM process obtained in this study compared to other studies.

Table 4: Comparison of cost estimation in SCM process (USD millions) and base catalyzed process (*cost index=585.7 year 2011)

	*This study	*This study	*This study	(Lee, S., 2001)	(Lee, S., 2001)
Plant capacity (tonnes/year in Million USD)	40000 (single step)	40000 (esterification)	40000 (propane)	40000 (single step)	40000 (base cat.)
Equipments	Jatropha curcas	Jatropha curcas	Jatropha curcas	Waste canola oil	Canola oil
Reactor	0.177	0.177	0.044	0.726	0.332
Methanol recovery	0.118	0.198	0.114	0.108	0.093
Biodiesel purification	0.324	0.850	0.066	0.227	0.186
Glycerol purification	-	-	-	-	0.065
Water washing	-	-	-	-	0.034
Pumps (*compressor)	0.046	0.023	*0.126	0.052	0.017
Heat exchangers	0.471	0.291	0.129	0.557	0.002
L-L separator	0.067	0.066	-	0.026	0.025
Flash evaporator	0.050	-	0.019	0.021	-
Equipment cost	1.25	1.61	0.50	1.72	0.772
Fixed capital cost	7.52	9.63	2.98	12.9	9.67
Working capital	1.13	1.45	0.45	1.94	1.45
Total capital investment	9.41	12.00	3.73	14.8	11.1
Raw material cost (yr^{-1})	15.25	14.79	15.31	23.12	39.88
Direct manufacturing cost (yr^{-1})	24.5	36.8	19.18	25.9	42.4
Indirect manufacturing cost (yr^{-1})	1.76	2.08	1.04	2.35	1.87
General and administrative cost (yr^{-1})	4.92	7.17	3.80	4.24	6.64
Biodiesel revenues (yr^{-1})	42.02	42.02	59.45	39.6	39.6
Credits for glycerine (yr^{-1})	5.80	5.80	4.10	3.45	5.49
Total production cost (yr^{-1})	31.20	46.02	24.02	32.49	50.9
Unit production cost (kg^{-1})	0.78	1.15	0.60	0.81	1.27

The glycerol credits in SCM-JCO single step, SCM-JCO esterification, SCM-JCO propane and base catalyzed were USD$ 5.80 million, USD$5.80 million, USD$4.10 million and USD$5.49 million, respectively, which SCM-JCO single step, esterification and base catalyzed were higher due than SCM-JCO propane and SCM-WFO due to the high purity of the glycerol. The cost of biodiesel in this study is USD0.78 kg^{-1}.

Compared to base catalyzed process, the unit production cost is USD 1.27/kg which is higher than the unit production cost via supercritical methanol process. The cost for raw materials is the major contributor due to the usage of fresh vegetable oil feedstock, the usage of larger amount of methanol, sulphuric acid catalyst and glycerol for washing solution in the liquid-liquid extraction column in the pre-treatment process. Besides that synthesis of biodiesel by an alkaline catalytic transesterification reaction has several drawbacks: it is energy intensive, recovery of glycerol is difficult, the alkaline wastewater retains fatty acids and water interferes with the reaction. In addition, alkaline transesterification is low in selectivity, leading to undesirable side reactions (Yin, J-Z., 2008). Furthermore, the highest total production cost was USD50.9 million for base catalyzed process while the base case of supercritical methanol by using Jatropha curcas oil was calculated to be USD31.20 million and SCM-JCO USD 24.02 million which the lowest among the processes.

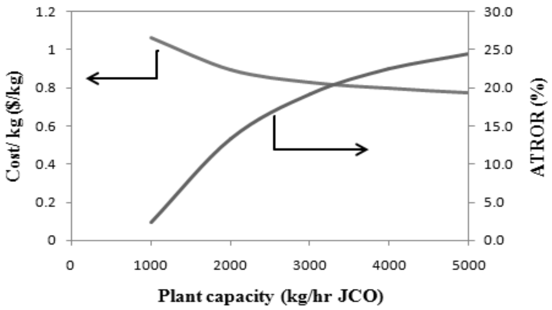

Fig. 2: Unit production cost as a function of plant production capacity and effect of plant capacity on ATROR

Finally, Figure 2 presents the unit production cost as a function of the biodiesel plant production capacity and the effect of plant capacity on ATROR. For production capacity as low as 8 $ktonneyr^{-1}$ the unit cost is estimated to be USD1.06 kg^{-1} and decreases sharply as production capacity increases up to 24 $ktonneyr^{-1}$. Further increases in the production capacity result in a less dramatic decrease in the unit cost, which approaches USD0.78 kg^{-1} as the production capacity approaches 40 $ktonneyr^{-1}$. Furthermore, as plant capacity is increased, the ATROR of the process increases. This implies that the increase in revenues gained from greater biodiesel production offsets the increase in TCI that results from increasing the scale of the plant.

Conclusion:

In conclusion, the results obtained are very promising, comparable and recommend that the supercritical methanol method has a high potential for the transesterification of JCO to methyl esters or biodiesel fuel.

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