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A comparative study on the membrane based palm oil mill effluent (POME) treatment plant

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ABSTRACT

The discharge of palm oil mill effluent (POME) causes serious pollution problems and the membrane based POME treatment is suggested as a solution. Three different designs, namely Design A, B and C distinguished by their different types and orientations of membrane system are proposed. The results at optimum condition proved that the quality of the recovered water for all the designs met the effluent discharge standards imposed by the Department of Environment (DOE). The economic analysis at the optimum condition shows that the total treatment cost for Design A was the highest (RM 115.11/m^3), followed by Design B (RM 23.64/m^3) and Design C (RM 7.03/m^3). In this study, the membrane system operated at high operating pressure with low membrane unit cost is preferable. Design C is chosen as the optimal design for the membrane based POME treatment system based on the lowest total treatment cost.

1. Introduction

The production of palm oil results in the generation of huge quantities of highly polluting wastewater termed as palm oil mill effluent (POME). The POME is thick brownish viscous liquid waste and non-toxic as no chemicals are added during oil extraction but has an unpleasant odor. It is predominantly organic in nature and highly polluting [1]. POME is a colloidal suspension of 95–96% water, 0.6–0.7% oil and 4–5% total solids including 2–4% suspended solids originating from mixture of a sterilizer condensate, separator sludge and hydrocyclone wastewater [2].

The conventional treatment technology of POME employed in most of the palm oil mills in Malaysia is the ponding system of biological treatment [3–5]. However, coping with the increasing production in most palm oil mills, the under-sized biological treatment system is unable to cope with the increased volume of POME [6]. Thus, proper POME treatment is urgently needed to ensure the sustainable economic growth of palm oil industry in Malaysia besides protecting the environment.

Several researchers have proposed other biological treatment system which includes aerated lagoon system [7], conventional anaerobic digester [8], anaerobic contact process [9], up-flow anaerobic sludge blanket (UASB) reactor [7,10], close tank digester [11], trickling filter [12], aerobic lagoon system[13], aerobic rotating biological contactor [14] and evaporation process [15]. However, the proposed biological treatment systems are only confined to lab scale analysis.

Membrane separation technology is recognized as an efficient, economical and reliable technology that exhibits high potential to be applied in POME treatment. The investigation on the feasibility and suitability of the membrane separation technology in POME treatment is carried out extensively in a pilot plant with the capacity of 450 L/h [2,16]. The pilot plant investigation is focused on the pretreatment system [17–19] and the membrane system [20–21]. The recovered sludge from pretreatment system can be used as fertilizer and the recovered water from the membrane system can be recycled as utility or boiler feed water. Looking at the promising results, there is an urgent need to develop and design an industrial scale membrane based POME treatment plant suitable for a typical palm oil mill in Malaysia based on the findings from the pilot plant investigation.

In the present study, three designs were examined and optimized for evaluation of performance and cost. Design A (Fig. 1) used ultrafiltration (UF) ceramic membranes and reverse osmosis (RO) polymeric membranes; Design B used UF polymeric membranes and RO polymeric membranes; and Design C had a two-pass RO polymeric membrane system. All three designs featured a pretreatment system consisting of equalization, cationic and anionic polymer flocculation, sludge dewatering using a dry solids decanter, and granular activated carbon (GAC) adsorption as shown in Fig. 1. Each of the proposed Designs A, B and C poses its specific advantages and disadvantages as summarized in Table 1. Consequently,

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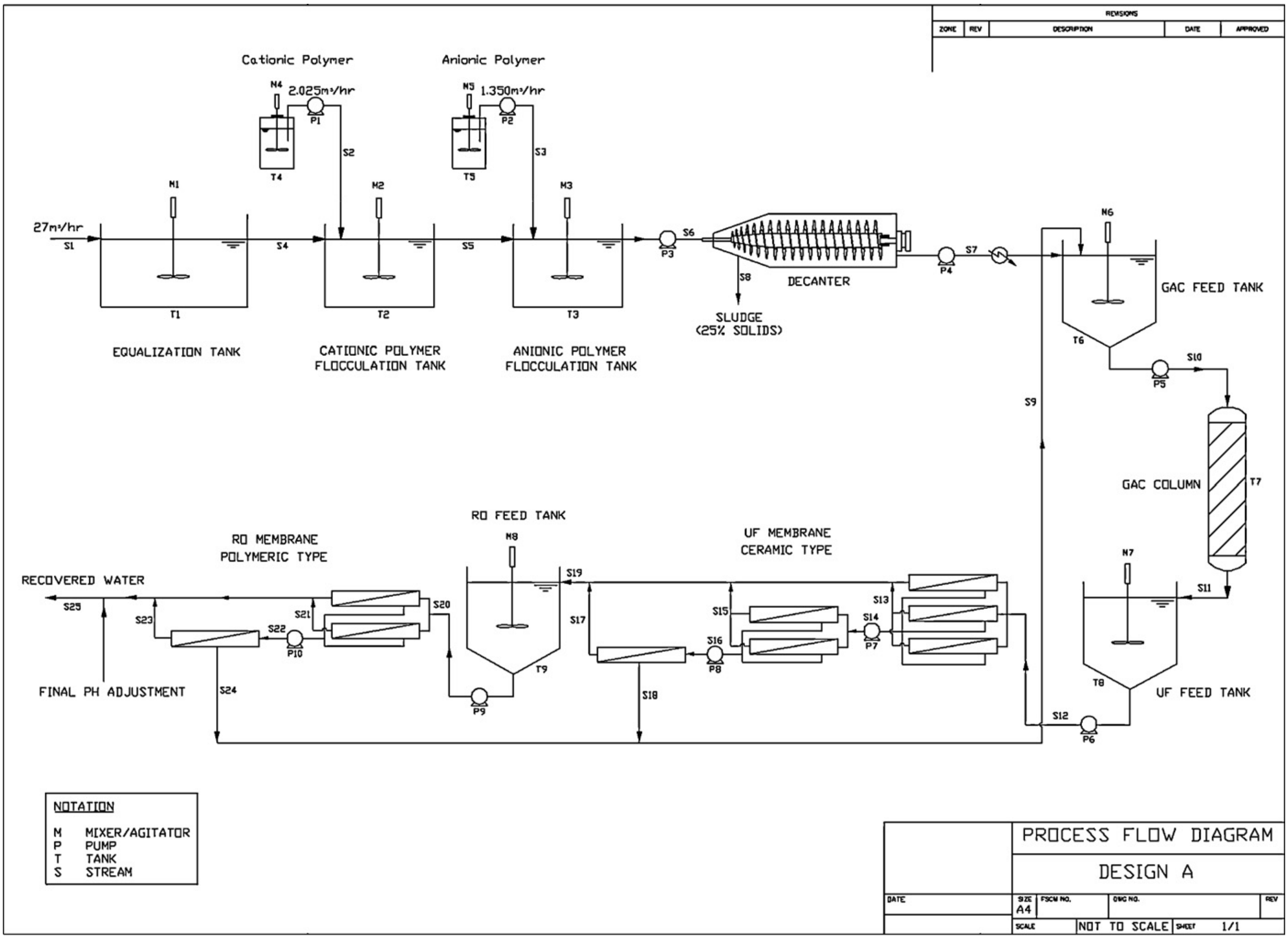

Fig. 1. Process flow diagram (PFD) of membrane based POME treatment system for Design A.

based on the qualitative comparison as shown in Table 1, the best design for the membrane based POME treatment is difficult to evaluate unless an optimization study is conducted so that the cost effectiveness for each design at the optimum condition is compared. The optimum condition for each design is obtained by using constrained nonlinear optimization based on the integrated transport models. Each of the Design A, B and C is optimized respectively, and the results pertaining to process economics in term of total costs are compared to identify the optimal process design.

Table 1
Comparison between the type of membrane used and the design of the process.

Membrane type	UF ceramic	UF polymeric	RO polymeric
Advantages	Offers long durability which can withstand excessive strong chemicals and high temperature, requires low trans membrane pressure.	Easy availability, offer larger effective filtration area, simple CIP procedure, cheap, requires low trans membrane pressure.	Much cheaper, well established, high pollutant rejection, large effective filtration area, simple CIP procedure and requires little cleaning reagent.
Disadvantages	Very expensive, small effective filtration area, require complex CIP procedure and much cleaning reagent.	Cannot withstand excessive strong chemicals and high temperature, not durable.	Cannot withstand excessive strong chemicals and high temperature, requires very high trans membrane pressure, not durable.
Design	A	B	C
Membrane system			
1st System	UF Ceramic	UF Polymeric	RO Polymeric
2nd System	RO Polymeric	RO Polymeric	RO Polymeric
Advantages	Require low energy cost, has long membrane life.	Require little membrane cleaning and low energy cost.	Low investment cost, requires very little membrane cleaning, produce very good water quality.
Disadvantages	Require very high investment cost and excessive membrane cleaning, produce only acceptable water quality.	Require high investment cost, produce only acceptable water quality, has short membrane life.	Require very high energy cost and has short membrane life.

Table 2
Cost parameters for membrane based POME treatment plant.

Cost parameters	Value/cost
Direct capital cost, DCC	
Tanks: atm, vertical cylinder, concrete	RM 1500 (0.55 m^3)[a]
Tanks: atm, vertical cylinder, HDPE	RM 546 (0.69 m^3)[a]
Tanks: atm, vertical cylinder, SS	RM 3000 (0.55 m^3)[a]
Agitator, turbine, top entry, open	RM 1700 (0.37 kW)[a]
Centrifugal pump	RM 5000 (0.32 kW)[a]
Piston pump	RM 14600 (27.73 kW)[a]
Dosing pump	RM 1400 (0.04 kW)[a]
Heat exchanger, shell-tube, floating head, C/S	RM 460 (1 m^2)[a]
UF membrane module, ceramic, SS housing	RM 16533 (0.36 m^2)[a]
UF membrane module, polymeric, SS housing	RM 4500 (0.9 m^2)[a]
RO membrane module, polymeric, SS housing	RM 2250 (0.9 m^2)[a]
Flow meter, digital type	RM 3000/unit[a]
Flow meter, analog type	RM 155/unit[a]
Pressure indicator, analog type	RM 120/unit[a]
Pressure control system (indicator, transmitter, controller)	RM 4100/unit[a]
Agitator inverter	RM 1700/unit[a]
Temperature indicator	RM 1400/unit[a]
Control panel	RM 9600/unit[a]
Wiring	RM 6500/unit[a]
Piping, valves and fitting	RM 27/membrane module[a]
CIP for membrane system	2% of membrane cost[b]
Indirect capital cost, ICC	
Indirect capital cost, ICC	10% of the direct capital cost, DCC[c]
Operating cost	
Maintenance cost, $C_{maintenance}$	6% of the annualized capital cost[b]
Electricity rate, c_{elec}	RM 0.258/kWh
Unit cost for cationic polymer, c_{chem}	RM 13.50/kg[d]
Unit cost for anionic polymer, c_{chem}	RM 12.70/kg[d]
Unit cost for activated carbon granular replacement, c_{GAC}	RM 1700/m^3[e]
Unit cost of UF membrane replacement, ceramic type, c_{memb}	RM 45,925/m^2[e]
Unit cost of UF membrane replacement, polymeric type, c_{memb}	RM 3889/m^2[e]
Unit cost of RO membrane replacement, polymeric type, c_{memb}	RM 1389/m^2[e]
Unit cost for sodium hydroxide, c_{NaOH}	RM 0.80/kg[f]
Unit cost for nitric acid, c_{HNO_3}	RM 1.50/kg[f]
Profit gained from fertilizer sale	
Selling price for fertilizer, c_{Fert}	RM 0.60/kg[g]

[a] The equipment size for the base cost obtained from Envilab Sdn. Bhd. is displayed in the parentheses.
[b] Wilf and Klinko [24].
[c] Helal et al. [27].
[d] Dia-Chemical Sdn. Bhd.
[e] Envilab Sdn. Bhd.
[f] Kong Long Huat Sdn. Bhd.
[g] Alfa Laval (Malaysia) Sdn. Bhd., exchange rate: 1 USD = 3.50 MYR as at 22 May 2009.

2. Transport models for membrane based POME treatment

The performance for each of the system/process in the pilot plant deals with specific internal mass balances as well as their equilibrium relationships, transport and thermodynamic properties which can be represented by the transport models. The transport models are also needed for mass balance calculation to estimate the performance, size and cost of the industrial scale membrane based POME treatment plant. In the present study, the transport models are developed for flocculation, granular activated carbon (GAC) adsorption, UF and RO membrane system. Overview and background of these transport models are summarized in the Appendix (Table A1). By connecting each process represented by its own transport model as presented in Table A1 at different membrane orientation, three membrane based POME treatment designs of A, B and C are delivered.

3. Cost estimation

In the present study, the cost estimation is made so that the total treatment cost could be compared between the Design A, B and C. The cost parameters and economic data used in cost analysis to estimate the direct capital cost (DCC), indirect capital cost (ICC), operating cost ($C_{operating}$) and profit gained from fertilizer sales (C_{Fert}) are displayed in Tables 2 and 3 respectively.

The exponential methods of order-of-magnitude estimate (ratio estimate) is used for the equipment cost estimation; which includes tanks, agitators, pumps, heat exchanger and membrane system. If the cost of a piece of equipment q_1 is C_1, then the cost C_2 of a similar piece of equipment q_2 can be calculated from

$$C_2 = C_1 \left(\frac{q_2}{q_1}\right)^{\zeta} \tag{1}$$

Table 3
Economic data for membrane based POME treatment plant.

Economic data	Value
Plant life, N_{yr}	20 years[a]
Inlet flow rate, Q_{in}	27 m^3/h[b]
Operation hours, t_h	16 h/day[b]
Operation days, t_d	315 days/year[b]
Interest rate, i	4%[a]
Capital recovery factor, CRF	0.0736[a]

[a] Wilf and Klinko [24].
[b] Alfa Laval (Malaysia) Sdn. Bhd.

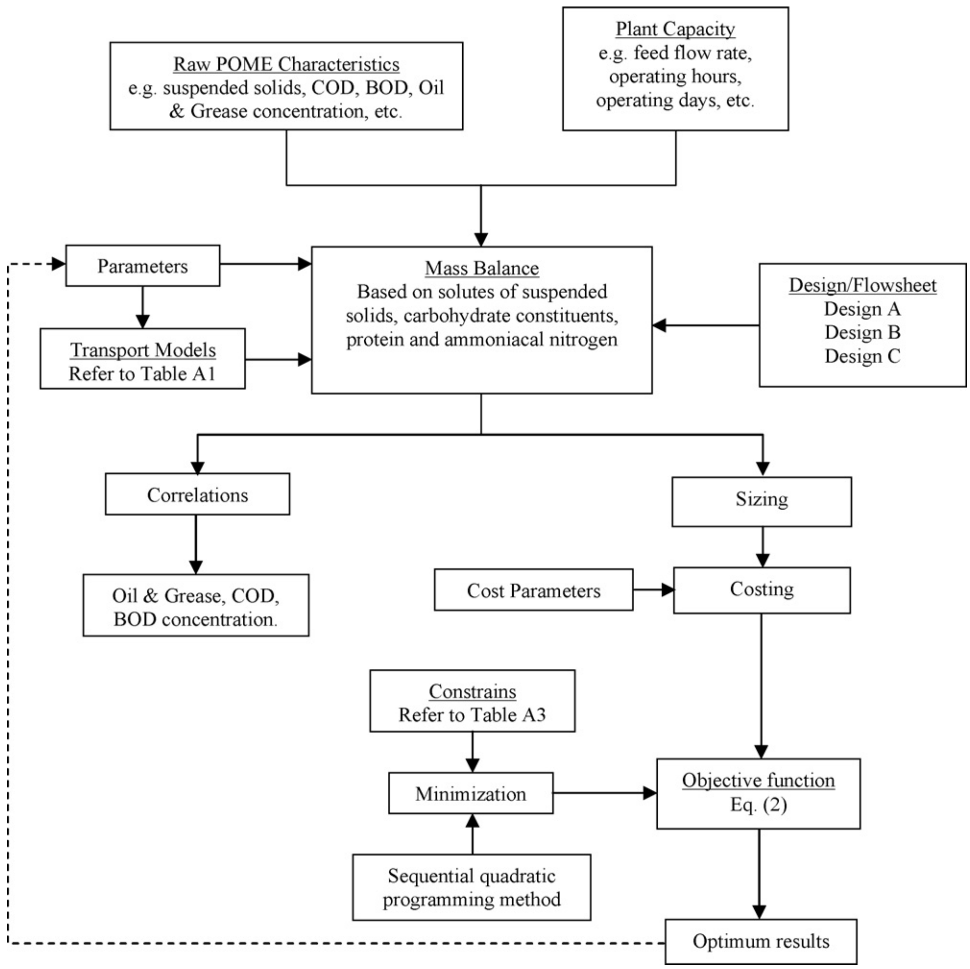

Fig. 2. Calculation and minimization of objective function flow diagram.

where the value of the exponent ζ depends on the type of equipment which can be obtained from Perry [22].

The operating cost of the system includes electrical cost, maintenance cost, chemical cost for cationic and anionic polymers, chemical cleaning cost for membrane system (sodium hydroxide and nitric acid), activated carbon granular and membrane replacement cost. The activated carbon granular replacement cost can be estimated by taking the annual replacement rate, ARR_{GAC} as 50%. For the UF and RO membrane, the membrane replacement cost can be estimated by considering the annual replacement rate, ARR_{memb}. The ARR_{memb} is taken as 50% and this value is higher than the ARR_{memb} reported by Wilf and Klinko [24] as 20%. Higher ARR_{memb} is given for the present study as the POME system exhibit high fouling rate in the membrane filtration compared to other system such as desalination of seawater and brackish water.

The total cost is the summation of annualized capital cost (ACC) and operating cost with the subtraction of profit gained from fertilizer sale. The ACC can be obtained as the product of total capital cost by the capital recovery factor (CRF).

4. Optimization and constraints

The objective of the optimization is to minimize total treatment cost per cubic meter of POME treated, c_{total} for the membrane based

Table 4
Properties of membrane small modules from PCI-Memtech, UK.

Property	UF membrane		RO membrane
Material	Ceramic	Polymeric	Polymeric
Module type	Tubular	Tubular	Tubular
$N_{memb,yr}$ or ARR_{memb}	5 years	50%	50%
Effective membrane area, A	0.36 m^2	0.90 m^2	0.91 m^2
Area of membrane channel, $A_{channel}$	0.03 m^2	0.05 m^2	0.05 m^2
Inner diameter of membrane tube, d	0.006 m	0.013 m	0.013 m
Number of membrane tubes, n	19	18	18
Membrane length, L	1.00 m	1.25 m	1.27 m
Number of membrane cleaning cycle, $N_{cleaning}$	48/year	24/year	24/year[a], 12/year[b]
Amount of caustic needed for CIP, m_{NaOH}	0.3 kg/module	0.3 kg/module	Not required
Amount of acid needed for CIP, m_{HNO_3}	0.3 kg/module	0.3 kg/module	0.042 kg/module

[a] for RO membrane of Design A and B and first pass RO membrane of Design C.
[b] for second pass RO membrane of Design C.

Table 5
Comparisons between the treated water for Designs A, B, and C with the effluent discharge standard imposed by DOE, Malaysia.

Parameter	Design A	Design B	Design C	Effluent discharge standard[a]
Temperature (°C)	30	30	30	45
Ammoniacal nitrogen (mg/L)	60	60	40	150
Suspended solids (mg/L)	ND	ND	ND	400
Oil and grease mg/L	ND	ND	ND	50
Total-nitrogen (mg/L)	<90	<90	<50	200
COD (mg/L)	263	275	114	[b]
BOD (mg/L)	88	92	38	100

[a] Thani et al. [7].
[b] No discharge standard after 1984; ND = not detectable.

POME treatment system. The objective function to be minimized; which is subjected to a set of decision variables, x as listed in the Appendix (Table A2) is presented mathematically by:

$$\min f(x) = c_{\text{total}} = \frac{\text{ACC} + C_{\text{operating}} - C_{\text{Fert}}}{Q_{\text{in}} t_{\text{d}} t_{\text{h}}} \quad (2)$$

The minimization of the objective function of Eq. (2) involves determination of the annualized capital cost (ACC), operating cost ($C_{\text{operating}}$) and profit gained from fertilizer sale (C_{Fert}). The terms Q_{in}, t_{d} and t_{k} are the inlet flow rate, operation hours and operation days. Determination and optimization (minimization) of these cost values are subjected to the calculation of transport models, mass balance, sizing and costing of the equipments as summarized in Fig. 2. It must be noted that the optimization in the present research is based on the total treatment cost minimization of a POME treatment plant instead of the total profit maximization of a palm oil mill. The treatment plant is a utility requirement to replace the conventional POME treatment system in an existing palm oil mill in order to meet the stringent effluent discharge standard imposed by the department of environment (DOE), Malaysia.

The upper limit and the lower limit allowed for each variable is the constraint imposed in the optimization calculation. For the membrane based POME treatment system, the constraints as listed in the Appendix (Table A3) are the operating conditions and physical limitations of the membrane system as well as the water quality requirement imposed by the DOE. As shown in the Table A3, the range of the constraints is the physical limitations of the membrane systems supplied by the membrane manufacturer, PCI-Memtech, UK. The membrane clean in place (CIP) cost is proportional to the total number of membrane modules at a fixed amount of caustic needed (m_{NaoH}), amount of acid needed (m_{HNO_3}) and number of membrane cleaning cycle (N_{cleaning}). However, the fixed m_{NaoH}, m_{HNO_3} and N_{cleaning} will become exponential functions in the conditions of high water recovery until the scaling and fouling become serious problems. In this condition, high chemical usage and very intensive membrane cleaning are required.

Table 6
Sizing and costing for the membrane system at optimum conditions.

	First membrane system			Second membrane system	
Design A	UF ceramic			RO polymeric	
Number of stages in series	3			2	
Overall recovery (%)	70			70	
Stage	1	2	3	1	2
Water recovery (%)	36.1915	35.9218	26.6275	53.0150	36.1498
Trans membrane pressure, (bar)	4	4	4	45	45
Outlet pressure (bar)	5.8	5.8	5.8	48	48
Membrane area (m^2)	540	342	163	363	117
Cross flow velocity (m/s)	0.5055	0.5093	0.6201	0.3126	0.3917
Equipment cost (10^3 RM)	24799.52	15706.37	7472.92	908.48	292.99
Energy cost (RM/year)	2716	1733	1419	112160	14291
Membrane replacement cost (10^3 RM/year)	5570.64	3528.06	1678.62	252.36	81.39
Chemical cleaning cost (RM/year)	49680	31460	14970	600	200
Design B	UF polymeric		RO polymeric		
Number of stages	2		2		
Overall recovery (%)	70		70		
Stage	1	2	1	2	
Water recovery (%)	49.8708	40.1546	53.0150	36.1498	
Trans membrane pressure (bar)	4	4	45	45	
Outlet pressure (bar)	5.1	5.1	48	48	
Membrane Area (m^2)	786	318	363	120	
Cross flow velocity (m/s)	0.2042	0.2388	0.3126	0.3917	
Equipment cost (10^3 RM)	3927.48	1588.95	908.48	292.99	
Energy cost (RM/year)	2716	1361	112160	14291	
Membrane replacement cost (10^3 RM/year)	1527.35	617.92	252.36	81.39	
Chemical cleaning cost (RM/year)	14490	5860	600	200	
Design C	RO polymeric		RO polymeric		
Number of stages	2		1		
Overall recovery (%)	70		70		
Stage	1	2	1		
Water recovery (%)	53.3463	35.6964	70		
Trans membrane pressure (bar)	45	45	45		
Outlet pressure (bar)	48	48	48		
Membrane area (m^2)	522	164	219		
Cross flow velocity (m/s)	0.3107	0.4167	0.5002		
Equipment cost (10^3 RM)	1305.94	408.92	547.36		
Energy cost (RM/year)	160229	20272	112160		
Membrane replacement cost (10^3 RM/year)	362.76	113.56	Nil		
Chemical cleaning cost (RM/year)	870	270	180		

Exchange rate: 1 USD = 3.50 MYR as at 22 May 2009.

Thus, the water recovery in every stage of membrane system, should not be more than 55% in order to maintain the m_{NaoH}, m_{HNO_3} and $N_{cleaning}$ at a fixed value [23]. The objective function of Eq. (2) also depends on the parameters, which are regarded as constants during the optimization calculation. The parameters used in the optimization calculations are mainly the raw POME characteristic, the cost parameters, economic data and the properties of membrane modules as listed in Tables 2–4 respectively.

It is well-known that the water recovery is the process parameter that has the largest effect on the capital and operating cost [24]. The water recovery is determined by the configuration of the membrane modules distribution, i.e., the number of membrane modules in series and in parallel, the number of stages in series, and trans membrane pressure [25]. Therefore, the optimization of the membrane based POME treatment process requires determination of these parameters values, which minimizes the total treatment cost subject to the technical constraints related to the maximum water recovery possible without irreversible fouling, jeopardizing the water quality and module physical limitations.

The system models for Design A, B and C were coded in MATLAB respectively and the constrained nonlinear problems are optimized using the sequential quadratic programming method [23]. The systems are minimized through the single-objective function which is total treatment cost per cubic meter, c_{total} of Eq. (2), subject to the constraints imposed on the variables as listed in Table A3. In each run, the starting values of cationic and anionic polymer dosage, residence time for activated carbon adsorption, water recovery and trans membrane pressure of each stage for first and second membrane system and number of small modules in series per pressure vessel/module of each stage in the membrane system are provided. For these set of values, the rejection/removal of all dissolved organic solutes and suspended solids for all the process of cationic and anionic polymers flocculation, GAC adsorption and membrane systems as well as the permeate flux for each stage of the membrane systems are computed based on the transport models. The water recovery of each stage of the membrane systems, the mass balance of the whole process and the cost values for Design A, B and C are then determined. The optimal values of the optimization variables were determined by the optimization tool of MATLAB. To increase the chance to obtain a global minimum of the total cost, the optimization procedure is repeated with several initial values of the optimization variables.

5. Results and discussion

The ultimate goal for the present study is to propose the best design for membrane based POME treatment plant suitable for the industrial scale operation. The best design should be cost effective and convincing to the plant's investor and at the same time meeting the requirement imposed by the Department of Environment (DOE).

5.1. Generalized findings

As mentioned earlier, optimization of the objective function is subjected to the simultaneous calculation of transport models, mass balance, sizing and costing of the equipments following the procedure shown in Fig. 2. Therefore, the mass balance, sizing and costing results presented in the present research are based on the optimum conditions. The mass balance of every process stream at the optimum condition is calculated based on the rejection/removal of all dissolved organic solutes and suspended solids for all the processes obtained from the transport models as summarized in Table A1.

Throughout the mass balance calculation, the overall water recovery for the first and second membrane system was fixed at 70% in order to obtain the optimum water recovery for each stage of the membrane system. In the common practice, the overall water recovery for multistage membrane system is often found through the optimization procedure. For desalination of seawater and brackish water using RO membrane system, the overall water recovery is 80–83% and 93–96% respectively [23]. The overall water recovery in the desalination process can be calculated through optimization procedure because the retentate stream from the final stage of the membrane is disposed off. In contrast to the present study, the retentate streams from the first and second membrane system are recycled back to the process and this requires extensive calculation. The global minimum is thus difficult to achieve because the overall water recovery is inter-link with the water recovery for every stage of the membrane system. It also requires longer computation time as it involves numerous iterations. Therefore, in the present study, it is adequate to fix the overall water recovery at 70%, a value slightly lower than the reported values as the POME system exhibits higher fouling potential than the seawater and brackish water system.

The quality of the recovered water for Designs A, B and C respectively as shown in Table 5 is meeting the Effluent Discharge Standard imposed by the DOE. The concentrations of total nitrogen, ammoniacal nitrogen, suspended solids, oil and grease in the recovered water for all the designs are well below the maximum allowable value. Although the BOD concentration obtained is well below the maximum allowable value for Design C, the BOD concentration obtained for the Design A and B is quite close with the maximum allowable value. Though this situation is acceptable, it is quite undesirable because it provides limited rooms for the case when the characteristic of the raw POME fluctuates.

The energy requirement for pumps is directly related to the operating pressure and the feed flow rate. As expected, the total energy cost for the two-pass RO system of Design C is the highest compared to the Designs A and B as shown in Table 6. Design B requires the lowest energy cost for the membrane system with the total energy cost of RM 130,528 per year. The energy cost for Design A is only 1.014 times higher than that of Design B but the Design C is 2.2 times higher. The energy cost for RO membrane system in Designs A and B constitute ∼96% of the total energy cost and this shows that the energy cost of the membrane system is highly depended on the operating pressure of the RO membrane system. High operating pressure is needed in the RO membrane system to overcome the average osmotic pressure.

As a generalized finding, the optimum water recovery at every stage of the first and second membrane system depicted a similar behavior. The objective function drives the optimal design in a direction that produces a large volume of permeate to obtain the possible maximum water recovery to offset the capital and operating cost. High water recovery can be achieved by applying high trans membrane pressure and/or increasing the membrane area. However, the optimization in the present study arrived at an optimum design that maximizes the water recovery by maximizing the trans membrane pressure and minimizing the membrane area. This shows that maintaining a high supply pressure is less costly than increasing the membrane area. The outlet pressure is limited to typical membrane manufacturer specifications that arise from the maximum pressure the membrane can withstand. In the present study, the optimum operating pressure obtained for every stage of the membrane systems as shown in Table 6 is at the upper limit pressure. The outlet pressure obtained for every stage in the membrane systems is close to the maximum allowable value. From Table 6, the optimum membrane area for every stage of the membrane system is obtained at the value close to the maximum allowable membrane modules in series with the number of membrane modules in parallel that produces the lowest cross flow

Table 7
Summary of the estimated cost breakdown for Design A, B and C.

	Design A	Design B	Design C
Direct capital cost (10^6 RM)			
Pretreatment	0.66	0.66	0.66
Membrane system	49.36	6.87	2.43
Framework	0.35	0.26	0.22
Automation and control	0.21	0.18	0.15
Piping, valves and fittings	0.10	0.05	0.03
CIP and back-flush system	0.98	0.13	0.05
Labor	0.18	0.11	0.07
Total	51.82	8.26	3.61
Indirect capital cost (10^6 RM)	5.16	0.81	0.34
Total capital cost (10^6 RM)	56.98	9.06	3.95
Annualized capital cost (10^6 RM/year)	4.19	0.67	0.29
Operating cost (10^6 RM/year)			
Electrical	0.22	0.22	0.38
Maintenance	0.25	0.04	0.02
Chemical	0.64	0.64	0.64
GAC replacement	0.04	0.04	0.04
Chemical cleaning	0.10	0.02	0.0013
Membrane replacement	11.11	2.48	0.48
Total	12.35	3.43	1.55
Profit gained from fertilizer sales (10^6 RM/year)	(0.88)	(0.88)	(0.88)
Cost per cubic meter (RM/m^3)			
Capital cost	30.81	4.90	2.13
Operating cost	90.77	25.22	11.37
Profit gained from fertilizer sales	6.47	6.47	6.47
Total cost (RM/m^3)	115.11	23.64	7.03

Exchange rate: 1 USD = 3.50 MYR as at 22 May 2009.

velocity which is close to the minimum allowable value. The similar findings of the present study were also reported in the optimization study of RO desalination plant by Maskan et al. [23] and Voros et al. [26]. They arrived at an optimum design that maximized the permeate recovery with high operating pressure and low cross flow velocity to maintain the membrane area at the minimum.

5.2. Overall optimal system cost

Based on the optimum operating conditions and design, the treatment cost for a plant capacity of 27 m^3/hr is estimated and the summary of the cost breakdown is presented in Table 7. All the Designs A, B and C which are operating at the optimum conditions are meeting the requirements and constraints as stated in Table A3. The results clearly shows that the total capital cost strongly depends on the cost of the membrane system which accounts for 95.2%, 83.2% and 67.3% of the total direct capital cost for Designs A, B and C respectively as displayed in Fig. 3. In other words, the unit cost and the type of the membrane used as well as the total membrane area needed are the important parameters that will determine the total capital cost.

The membrane replacement cost gives the most significant influence to the operating cost for the Designs A and B which account for 89.9% and 72.1% of the total operating cost respectively (Fig. 4). However, the chemical cost used for pretreatment (namely cationic and anionic polymers cost) gives the most significant influence to the operating cost for Design C (41.0%). This scenario is indirectly related to the type of the membrane used as the unit costs of the UF membrane system for both ceramic and polymeric types are more expensive than the unit cost of RO membrane system. The unit cost of membranes is based on the price quoted by Envilab Sdn. Bhd. as shown in Table 2.

The estimated total cost per cubic meter as shown in Table 7 depicts that operating cost of the process for Design A, B and C which accounts for 74.7%, 83.7% and 84.2% of the total cost played a very important role in determining the total treatment cost. The observed results indicate that further reduction in the operating cost can contribute strongly to reducing the total treatment cost. By comparing the estimated total cost per cubic meter at the optimum conditions between Designs A, B and C, the total cost for Design C is the lowest, which is 7.03 RM/m^3. In contrast, the estimated total cost per cubic meter for Design A is too high as compared to the other designs. This shows that in the present study, the membrane system operated at high operating pressure with low membrane unit cost

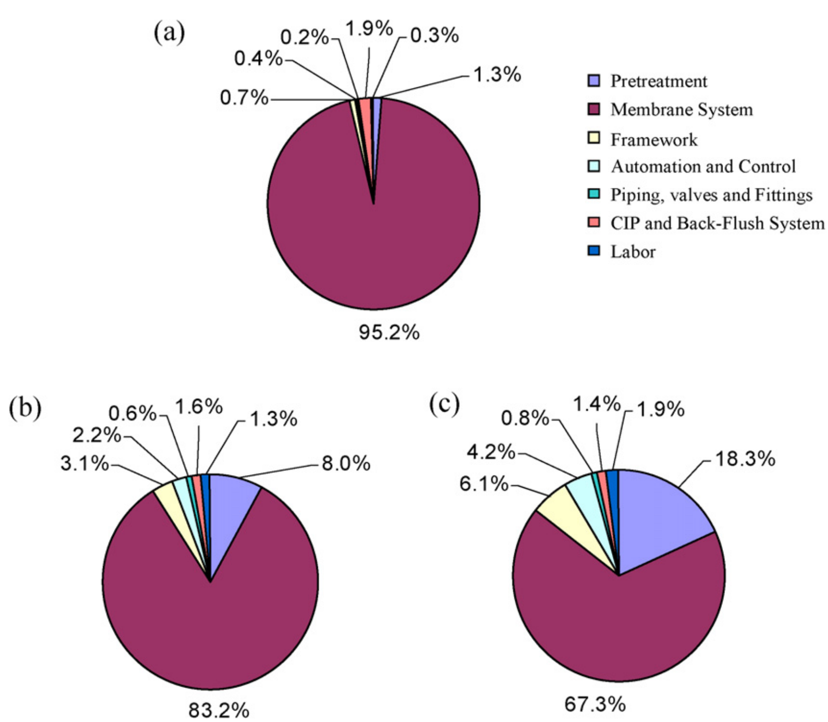

Fig. 3. Cost breakdown in term of percentage for the total direct capital cost of (a) Design A, (b) Design B, and (c) Design C.

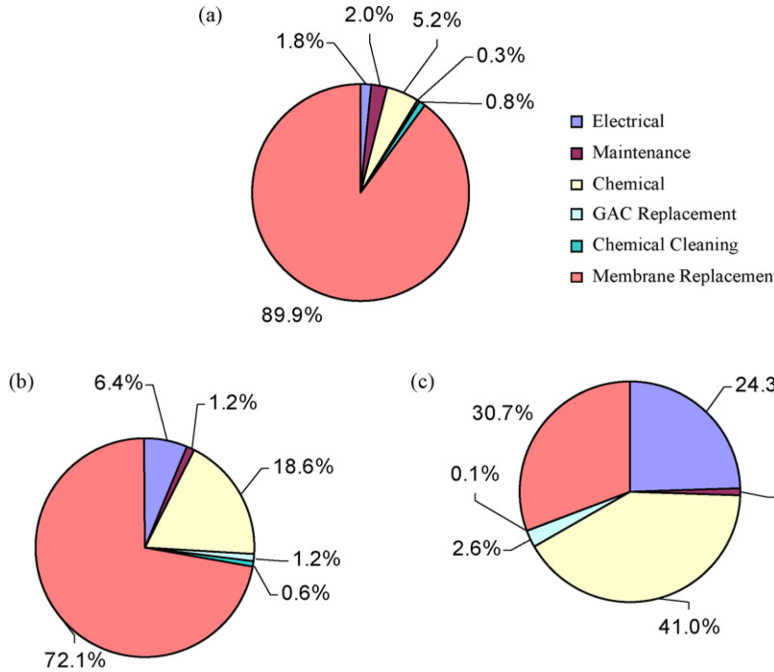

Fig. 4. Cost breakdown in term of percentage for the total operating cost of (a) Design A, (b) Design B, and (c) Design C.

is preferable compared to the membrane system operated at low operating pressure with high membrane unit cost. Therefore, the Design C is chosen as the optimal design for the membrane based POME treatment system.

6. Conclusions

Three different designs (namely Design A, B and C) of industrial scale membrane based POME treatment plant were investigated. The comparison based on the total treatment cost between Designs A, B and C was greatly influenced by the choice of membrane system used. The optimization for the Designs A, B and C arrived at an optimum condition that maximizes the water recovery by maximizing the trans membrane pressure and minimizing the membrane area because maintaining a high supply pressure is less costly than increasing the membrane area. At the optimum condition, the cross flow velocity was maintained close to the minimum allowable value for all the Designs A, B and C.

The results obtained at optimum condition showed that the quality of the recovered water for Designs A, B and C met the effluent discharge standards imposed by the DOE. The sizing and costing analysis based on the optimum condition show that the total treatment cost per cubic meter of POME treated at the optimum condition for Design A was the highest (RM115.11/m^3), followed by Design B (RM23.64/m^3) and Design C (RM7.03/m^3). As a result, Design C was chosen as an optimal design for the membrane based POME treatment system.

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