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Optimal Design of Integrated Palm Oil Complex with Palm Oil Mill Effluent Elimination Strategy

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Palm oil mill effluent (POME) is one of the biggest pollution sources due to its eutrophying nature and methane emitting treatment technology. Although biogas capture and utilisation have been widely encouraged to achieve greenhouse gas (GHG) mitigation in palm oil mills (POM), most Malaysian POMs still find it economically infeasible to invest in proper biogas facilities. Hence, POME elimination should be considered as one of the waste management options in synthesising palm oil processing pathway for profit enhancement and GHG mitigation. One of the solutions to achieve sustainability in palm oil industry is to integrate POM and palm oil refinery (POR) in terms of waste management, energy and resource. Therefore, it is desired to design an optimally integrated palm oil based-complex (POBC) which considers POME evaporation approach. The main objective of this study is to develop a model to aid POBC planning via synthesis of an integrated resource and utility network considering POME elimination with maximum profit. Based on the case study, maximum USD 36.65 x 10^6 is obtained for the optimal POBC design with POME elimination pathway selected. The optimum production rate for Refined, Bleached, Deodorised Palm Olein (RBDPOL) is 10.309 t/h which is boosted compared to the baseline study. 61 % less water demand is also achieved. The research output, the developed model and optimal network shall provide input to POM owners on optimal POME management and determine the economic feasibility of proposed POBC in Malaysia.

1. Introduction

There is no doubt that palm oil industry has been generously contributing to Malaysia's gross domestic product (GDP) with roughly MYR 80 x 10^9 achievement recorded in 2018 (Mohtar et al., 2017). The on-going crisis regarding oil palm sustainability due to global warming contributions associated with palm oil mill (POM) waste treatment affects the palm oil market negatively. The conventional palm oil milling practices applied in Malaysian POMs generate an enormous amount of liquid waste termed palm oil mill effluent (POME) which has a polluting nature (Rahman et al., 2019). Anaerobic digestion is the most common solution for POME treatment but is associated with greenhouse gas (GHG) emission in the form of methane-contained biogas released at open pond. The fact that the global warming potential (GWP) contributed by annual POME production in Malaysia approaches 9.3 % of the country's fossil fuel emission in 2012 has proven the criticality of this issue (Vijaya et al., 2008). Previous researchers have attempted to reduce the GWP of anaerobic POME treatment by encouraging biogas capture and applications such as on-site steam and power conversion and off-site utilisation (Mohtar et al., 2017) for profit enhancement. Only 25 % of Malaysian POM has reported adequate biogas facilities by 2018, indicating ineffective overall methane reduction (Ahmed et al., 2015). The low popularity of biogas utilisation may be due to several factors: a) high investment cost of effective biogas facility, b) uncertainty of biogas plant production due to seasonal POME quality variations, c) land requirement for biogas plant installation. In this scenario, other POME management practices such as POME elimination should be considered in substitution of conventional POME treatment. Instead of recovering POME waste value via biogas applications, eliminating and minimising POME generation could be the sustainable POME handling solution.

A new clarification procedure for palm oil has been proposed by Kandiah and Batumalai (2013) which consists of a series of processes that can result in 83 % POME reduction by reducing the clarification effluent and

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subsequently evaporates the remaining liquid effluent using multiple-effect evaporator. The process condensate exiting the evaporator can be recovered as utility water for mill operations whereas the process concentrate undergoes solvent extraction to recover trapped oil and exit as marketable decanter solid with zero effluent discharged. The POME elimination strategy not only eliminates the cost of POME treatment and biogas trapping facilities but also contributes to methane avoidance and freshwater demand minimisation.
Another solution in enhancing palm oil sustainability is industrial integration within the palm oil supply chain. The concept of integration has been applied previously between POM and biomass-based biorefinery. Kasivisvanathan et al. (2012) have proposed a modelling method for retrofitting a POM into an integrated biorefinery. Abdul Hamid and Lim (2018) investigated the techno-economic benefits of integrating a POM with an algae-based biorefinery by feeding biogas effluent to algae cultivation. Industrial integration can also be optimised in the form of an integrated process complex. Ng et al. (2013) described their idea of synthesising an integrated palm oil processing complex (POPC) that achieves material exchange between POM, refinery, palm-based biorefinery and CHP system as individual blocks (Ng and Ng, 2013).
No work has yet considered POME evaporation and water utility network in the pathway synthesis of an economically optimised integrated palm oil-based complex. To fill the existing gaps, an integrated palm oil based-complex (POBC) is outlined to optimise material, waste and utility exchange between POM and palm oil refinery (POR) with consideration of POME elimination approach. The synthesis of an optimum POBC can help to improve the profit margin and quality of refined palm oil end products. Hence, this work proposes a mixed integer linear programming model to optimise the configuration of POBC and investigate the economic feasibility of POME elimination practice in Malaysia. If proven feasible, the proposed POBC can be an alternative solution for existing or future POM owners to comply with Malaysia's methane avoidance policy.

2. Method

2.1 Problem statement

Given a set of resources *i* and potential technologies *p* for palm oil milling and refining (*y1* POME elimination and *y2* POME generation configuration), biomass-to-energy conversions and biogas applications, economic data (technology capital and processing cost, resource cost, utility cost and product price), process and operating data for each technology (conversion yield, capacity, utility and material requirement), the problem consists of optimising: a) the product portfolio and pathway selection of a POBC b) overall economic performance in terms of economic potential, with the objective function of maximising economic potential.
By solving the optimisation problem with the objective function of maximising economic potential, the resulted production portfolio should allocate the optimum material flowrates within the POBC whereas the process pathway consists of the chosen technologies with respect to the type of POME management approach selected by the optimisation tool. This work is expected to assist the enterprise to synthesise the optimum configuration of a POBC with respect to maximum economic performance.

2.2 Model development

For this study, set *p* denotes the type of process whereas set *i* denotes the type of resource. The material balance for the POBC model is adapted from the work of Lim et al. (2014). The amount of resource (RES_i) existing in the system can be either the total self-generated resource ($SGRES_{i,p}$) produced from different process *p*, or total external resource ($EXRES_i$) imported, as shown in Eq(1). Subsequently, these resources can be utilised by the system as feed resource ($MAT_{i,p}$) for each specific process or sold to market as product (PRO_i), as represented by Eq(2).

$$RES_i = \sum_p SGRES_{i,p} + EXRES_i \ \ \forall i \tag{1}$$

$$RES_i = \sum_p MAT_{i,p} + PRO_i \ \ \forall i \tag{2}$$

Intermediate resource indicator ($BYIND_i$) is assigned as a binary parameter to ensure certain intermediate products from specific processes are fully consumed by the subsequent process. $BYIND_i$ is declared as 0 for intermediate resource. Eq(3) is declared to ensure the intermediate resource is not retained in the system as product where an infinitely large value, 1000, is multiplied with the binary parameter to perform linearization.

$$PRO_i \leq 1000 \times BYIND_i \ \ \forall i \tag{3}$$

Eq(4) and Eq(5) represent the limiting constraints for product demand and external resource. The amount of product (PRO_i) should not be less than the designated product demand ($DEMPRO_i$) whereas the quantity of external resource ($EXRES_i$) should not be more than the resource availability ($AVRES_i$).

$$DEMPRO_i \leq PRO_i \ \ \forall i \tag{4}$$

$$EXRES_i \leq AVRES_i \ \ \forall i \tag{5}$$

The quantity of resource i fed into process p, $MAT_{i,p}$, is determined by the material conversion matrix ($MCM_{i,p}$) and the total amount of the resource fed into process p ($PRES_p$), as shown in Eq(6). Eq(7) describes the conversion of total fed resource to self-generated resource ($SGRES_{i,p}$) from the respective process based on the process resource conversion matrix, $PRCM_{i,p}$ (Lim et al., 2014).

$$MAT_{i,p} = MCM_{i,p} \times PRES_p \ \ \forall i\, \forall p \tag{6}$$

$$SGRES_{i,p} = PRCM_{i,p} \times PRES_p \ \ \forall i\, \forall p \tag{7}$$

The number of process units (cap_p) assigned for each process *p* is based on the limiting design capacity ($descap_p$) of certain reference resource *i* associated with each process *p* as shown in Eq(9). With reference to Eq(8), the binary indicator ($yref_{i,p}$) identifies the reference resource and is assigned as 1 if the amount of feed resource ($MAT_{i,p}$) or self-generated resource ($SGRES_{i,p}$) limits the capacity process *p*.

$$capres_p = \sum_i (yref_{i,p} \times MAT_{i,p}) + \sum_i (yref_{i,p} \times SGRES_{i,p}) \ \ \forall p \tag{8}$$

$$cap_p \times descap_p \geq capres_p \ \ \forall p \tag{9}$$

$y1$ and $y2$ are the binary variables to choose either POME generation or POME elimination pathway. Eq(10) to Eq(13) are declared to ensure the feed resource for POME utilisation and POME elimination pathway is only consumed for either one pathway. In Eq(10)-(13), $UDPLFLOW$ is the total amount of resource $i = 18$, undiluted PL converted from POME via process $p = 12$ therefore is multiplied with $y2$, whereas the amount of resource $i = 8$, diluted PL produced via process $p = 5$ for the POME utilisation milling configuration is multiplied with $y1$. Similarly, the amount of undiluted POME generated that will be treated in the POME elimination pathway and amount of sterilizer POME converted from POME which will be fed to digester are assigned to $y2$ and $y1$. Due to the multiplication of positive variable and binary variable, linearization is performed by multiplying the binary variables with large value to avoid complexity. Note that the PORE generated from POR can only be fed into the POME elimination considered process pathway, otherwise will be treated via SBR.

$$UDPLFLOW = SGRES_{i=18,p=12} \tag{10}$$

$$UDPLFLOW \leq 1000 \times y2 \tag{11}$$

$$DPLFLOW = SGRES_{i=8,p=5} \tag{12}$$

$$DPLFLOW \leq 1000 \times y1 \tag{13}$$

The total electricity demand in MWh ($ELECDEM$) is obtained by multiplying unit power demand ($UELECDEM_p$) for each technology with cap_p as described in Eq(14). In Eq(15), the excess power generated ($EXCESSELEC$) and overall electricity demand are balanced by system-generated electricity ($PRO_{i=31}$) and external power purchased (EXELEC). The electricity revenue and cost are calculated by multiplying with the price and cost as shown in Eq(16) and Eq(17).

$$ELECDEM = \sum_p (UELECDEM_p \times cap_p) \tag{14}$$

$$ELECDEM + EXCESSELEC = \mathrm{EXELEC} + PRO_{i=31} \tag{15}$$

$$ELECREV = \ \ EXCESSELEC \times ELECPRICE \tag{16}$$

$$ELECCOST = \mathrm{EXELEC} \times URCOST_{i=31} \tag{17}$$

The main objective of the developed model is to maximise the economic performance (EP) of the POBC as described in Eq(18). Note that a positive EP value indicates an economically feasible design (Foong et al., 2019). The capital recovery factor (crf) is included to annualise capital costs based on the operation lifespan. Gross profit (GP), total capital cost (CAPEX) and process operating costs (OPEX) can be calculated using

Eq(19)-(21). Economic parameters such as annual operating hours (AOT), unit processing cost ($UOPEX_p$), unit capital cost ($UCAPEX_p$), unit product price ($PRICE_i$) and unit material cost ($URCOST_i$) are based on case study.

$$EP = \mathrm{GP} - \mathrm{CAPEX} \times crf \tag{18}$$

$$GP = \mathrm{AOT} \times (\textstyle\sum_i PRO_i \times PRICE_i - \sum_i EXRES_i \times URCOST_i + \mathrm{ELECREV} - \mathrm{ELECCOST}) - \mathrm{OPEX} \tag{19}$$

$$\mathrm{CAPEX} = \textstyle\sum_p cap_p \times UCAPEX_p \tag{20}$$

$$\mathrm{OPEX} = \textstyle\sum_p cap_p \times UOPEX_p \tag{21}$$

3. Case study

The developed model is applied to a case study presented based on information collected from literature, technology provider and Malaysian palm oil industry. In this case study, a potential palm oil enterprise in Malaysia is interested to retrofit an existing POM into a methane avoidance POBC with maximum economic performance (EP) and achieve possible integration with its existing POR producing RBDPOL as main product, RBDPS and PFAD as by-products. The general process flowsheet for the POBC is shown in Figure 1. The dashed borders group the unit operations into important sections within the POBC.

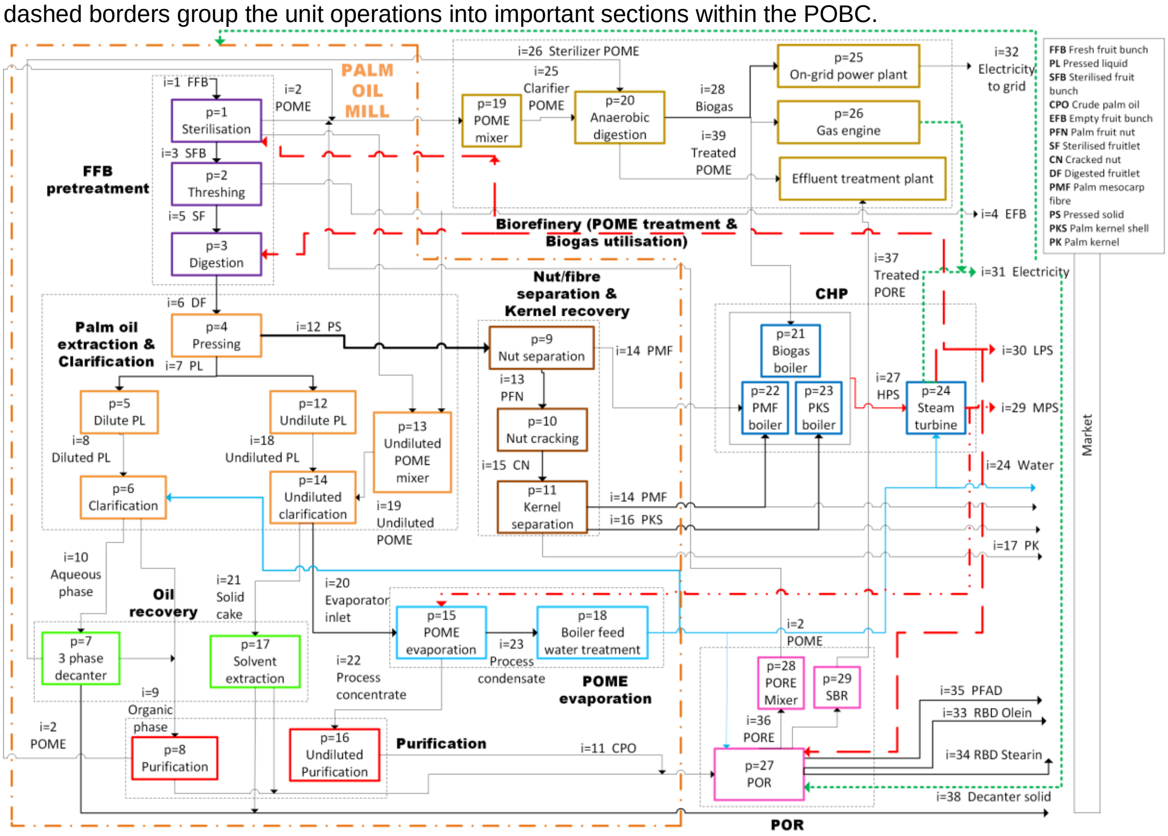

Figure 1: The possible configurations of a POBC

The palm oil enterprise is operating a POM with 60 t/h capacity for 12 h daily with fresh fruit bunches (FFB) supplied by its oil palm plantation. Crude palm oil (CPO) is extracted from FFB via a series of palm oil milling processes as the main product of the POM. By-products such as empty fruit bunches (EFB), palm kernel (PK), palm mesocarp fibre (PMF), palm kernel shell (PKS) and decanter solid, can either be sold directly to the market or utilised for utility generation. The thermal energy and electricity required by the mill can be imported or supplied by a Conventional heat and power (CHP) system consists of biomass boilers and steam turbine using PMF and PKS as boiler fuel. POME generated from the POM is conventionally treated in anaerobic ponding system. Due to Malaysia's methane avoidance policy, the enterprise is required to retrofit the POM

with methane mitigation strategies. The configuration of the retrofitted POM can be decided based on two types of POME management approach, POME utilisation or POME elimination scenario.
In the POME utilisation pathway, POME generated from sterilisation, diluted clarification and kernel separation processes will be treated in anaerobic digester tank to produce biogas before delivering to the treatment plant. Biogas applications for selection include on-site electricity generation via gas engine, on-grid biogas power plant and co-firing with biomass for utility generation. The revenue from on-grid biogas power plant is based on Malaysian Feed-in tariff (FiT) rates.
For POME eliminated configuration, POME evaporation and solvent extraction units are required, and undiluted clarification method is applied on existing clarification unit. POME from each unit is fed into the undiluted clarification unit and subsequently evaporation unit to achieve zero effluent discharge. The process condensate exits from the POME evaporation unit (double-effect evaporator) can be regenerated as water utility via boiler feedwater treatment. The process concentrate is further processed into decanter solid after oil recovery via solvent extraction. External water demand for steam generation is supplied by the nearest river source.Note that only one type of pathway configuration can be chosen. Thus, it is important to screen the pathways to synthesise an optimal POM complex configuration for the enterprise.
The palm oil enterprise also operates a POR with production demand of 10 t/h Refined, Bleached, Deodorised Palm Olein (RBDPOL) as main product, Refined, Bleached, Deodorised Palm Stearin (RBDPS) and Palm Fatty Acid Distillate (PFAD) as by-products. The POR plant includes physical refining processes and fractionation technology to process CPO purchased from external sources. The CPO produced from the mill can be directly fed into POR for refined palm oil products production to improve the profit margin. The water, steam and electricity demand of POR can be supplied by the CHP system in the retrofitted POM. The palm oil refinery effluent (PORE) generated from the POR can be treated via POME evaporation unit in the POM or sequential batch reactor (SBR) before being sent to the effluent treatment plant. Some useful economic parameters and pricing of important products considered in this case study are obtained from literature (Foong et al., 2019). The operational life span of the POBC is 15 y hence the capital recovery rate, crf is 0.096. The annual operating hour for the POM is 4,350 h/y. The import price for external CPO is 492 USD/t whereas the selling price for RBDPOL is 515.76 USD/t.

4. Results and discussion

The case study is solved by the developed mixed integer linear programming (MILP) model and optimised in the General Algebraic Modelling System (GAMS) software (version 24.7.4) using the CPLEX solver (12.6.3.0). A POBC with optimised economic performance is designed with the product portfolio and pathway configuration as shown in Figure 2.

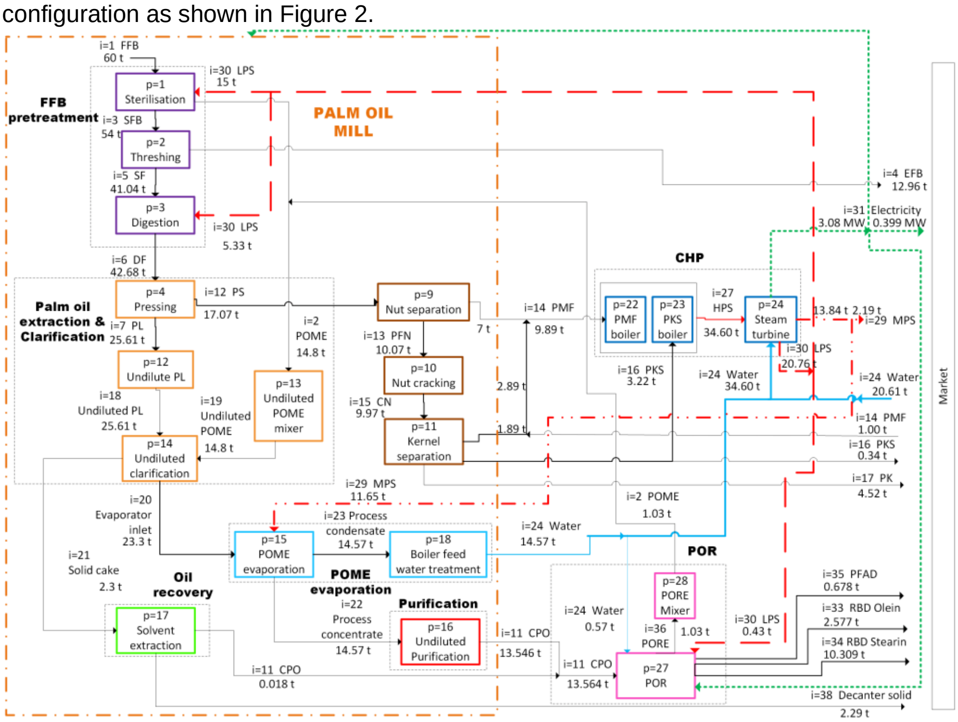

Figure 2: The optimum POBC flowsheet for applied case study

The material flowrates are given on an hourly basis. The POME elimination pathway is selected as indicated by $y2 = 1$ hence all POME and PORE generated are treated in the undiluted clarification and POME evaporation process. No final POME is discharged, and no biogas is generated for utilisation. Integration between POM and POR is achieved as the 13.564 t of CPO produced by POM is fed into POR to produce 10.309 t of RBDPOL, 2.577 t of RBDPS and 0.678 t of PFAD. The maximum EP is obtained as USD 36.65 x 10^6, where the revenue is boosted by the additional production of RBDPOL, RBDPS and PFAD processed from self-generated CPO. This is due to the improved oil extraction rate (OER) associated with the POME elimination pathway. In terms of utility generation, 8.89 t of PMF and 3.22 t of PKS produced are being consumed as boiler fuel for the CHP system consists of biomass boilers and steam turbine. To satisfy the LPS demand, additional 1 t/h of PMF is imported at 23 USD/t for steam generation. After satisfying the POBC utility demand, excess 0.399 MWh of electricity generated can be sold. EFB, PK, remaining PKS, decanter solid are sold as by-products for additional revenue. The water demand of POBC is satisfied by 14.57 t of regenerated water and external 20.61 t freshwater purchased. The model is also applied to a baseline POBC case study with only POME utilisation pathway considerations. The optimised results for the baseline study gave a lower EP (USD 36.50 x 10^6) due to the lower CPO production rate from the conventional palm oil processing technologies and high capital cost for biogas facilities. Although the baseline study generates excess 0.572 MWh of electricity, the freshwater demand is 61 % higher compared to the optimum POME eliminated POBC due to higher usage of water and no water regeneration opportunity.

5. Conclusions

A MILP model for an optimum POBC design with respect to maximum economic performance is developed. The model is capable of aiding the decision maker in designing the optimal configuration for retrofitting an existing POM into POBC or constructing a new POBC with consideration of POME elimination approaches as well as material, utility and waste integrations with POR. The selected POBC pathway configuration is based on cost and efficiency. Note that results may differ according to variations in product prices, technology efficiencies, processing and capital costs in different scenarios. This study has proven the economic feasibility of retrofitting a methane emitting POM into POME eliminated POBC while the results and model can guide Malaysian potential and existing POM owners in considering POME elimination approach over biogas utilisation. In future, environmental aspects should be considered to develop a multi-objective model that demonstrates the environmental feasibility of the proposed POBC and optimises the trade-offs between economic and environmental concerns in the design of POBC.

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