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Comparative Assessment for Mechanical Vapour Recompression and Multi-effect Evaporation Technology in Palm Oil Mill Effluent Elimination

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Due to the alarming methane emission from anaerobic palm oil mill effluent (POME) treatment practices in palm oil mills, POME elimination strategy is considered as an alternative zero waste solution towards methane mitigation apart from biogas recovery. By dewatering the effluent, POME evaporation technology provides opportunities in water recycling, oil recovery, effluent elimination and process integration with downstream refinery. One of the challenges for implementing POME evaporation is the extensive thermal energy use, which threatens energy efficiency and carbon footprint of palm oil mill. Advanced technologies such as multi-effect evaporation (MEE) and mechanical vapour recompression (MVR) can be considered to reduce steam demand for POME evaporation. Recently, electrical-driven MVR evaporator emerges as a popular solution for solution concentration and food powder production. In MVR systems, evaporated vapour is recompressed by power-consuming mechanical energy to enable steam reuse and reduction in fresh steam demand. In this paper, MEE and MVR evaporation systems are considered for POME dewatering in the integrated palm-oil based complex (POBC) optimisation. A fuzzy multi-objective optimisation model was developed to evaluate the trade-offs of economic benefits, energy consumption and environmental impacts between thermal and electrical driven evaporation techniques for sustainable POBC design. MEE was selected in the fuzzy optimal POBC with aggregate satisfaction of four objectives and improved the EP and GHG reduction of baseline study by 12 % and 61 %. Single-effect MVR POME evaporator contributed to 64 % thermal cost savings with overall 1.5 % reduction in POBC profitability. The optimal results and electricity-to-steam (ETS) price analysis have provided critical insights into the feasibility of MEE and MVR evaporation in POMs. Reducing electricity tariff to achieve ETS ratio below 1.27 could increase the economic favourability of MVR-implemented POBC.

1. Introduction

Palm oil mill effluent (POME) is known as a source of contribution towards climate change and water pollution during the production of crude palm oil (CPO) in palm oil mills (POMs). Standing as the second-largest palm oil producer internationally, Malaysia enforces its POMs to treat POME with greenhouse gas (GHG) mitigation strategy. Although capturing biogas released from the biological treatment of POME has been commonly encouraged to achieve methane avoidance, recently POME evaporation has shown great potential in converting POME to a marketable solid on top of undiluted clarification and oil recovery (Alfa Laval, 2018). This alternative technology to eliminate POME could contribute reduction in environmental footprints besides lower capital investment in comparison to biogas facilities (Tan and Lim, 2019). One of the challenges for implementing POME evaporation in POM is the extensive thermal energy use, posing new challenges in energy efficiency. To increase the favourability of POME evaporation, advanced technologies to reduce steam demand should be investigated. In the POME evaporation attempt of Kandiah and Batumalai (2013), multi-effect evaporator (MEE) has replaced single-effect evaporator to reduce up to 75 % of steam requirements

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with investment for additional effects. It was suggested that incorporation of mechanical vapour recompression (MVR) technology in single-effect evaporators could achieve lower steam requirement compared to MEE. MVR technology is suitable for applications with low boiling point elevation such as POME evaporation. In an MVR system, vapour from the evaporation-side of the unit is recompressed by a specialised fan driven by electrical energy to enable reuse of vapour and eliminate steam consumption during operation (Walmsley et al., 2016). Electrical-driven MVR evaporation systems have been commercialised for wastewater treatment such as desalination and milk powder production (Ai et al., 2019). 67 % improvement in energy efficiency has been demonstrated by Walmsley et al. (2016) through the optimal application of MVR technology to milk evaporator systems. Walmsley et al. (2017) also considered MVR integration for black liquor concentration at Kraft mills using a Total Site Heat Integration (TSHI) lens. Although MVR evaporation system was proven efficient in optimal site heat integrations for the reported case studies, MVR applications in POME evaporation has yet been studied. The trade-offs between steam savings and expensive capital for MVR implementation as well as high electrical charges for mechanical compressor are the key factors to be evaluated in choosing the optimal technology for any evaporation system. Ahmetović et al. (2018) studied the energy and capital costs trade-offs for single-effect, MEE and MVR evaporation systems using a mixed-integer non-linear programming (MINLP) model. The work of Ai et al. (2019) showed 73.5 % of energy savings in economic feasible MVR solution regeneration system when compared to MEE. To date, no optimisation study has addressed the energy, economic and environmental effects of integrating MVR evaporation system in a POME-eliminated POM. To address sustainability concerns, the selection criteria for POME evaporator should include its contribution to the EP, net energy, GHG and water footprint (WFP) of POM. This study aims to fill the gap in the palm oil-based complex (POBC) optimisation work of Tan et al. (2020a) by investigating the trade-offs of MEE and MVR technologies for energy reduction in POME evaporation to achieve sustainable POBC with optimal utility integration. By considering these factors, the objective of this work is to determine the optimal flowsheet of POBC retrofitted from POM, with choices of MEE and MVR technologies in POME dewatering, subjected to four optimisation objectives: economic potential (EP), net energy, GHG footprint and WFP using a fuzzy optimisation approach. Comparative assessment between MEE and MVR evaporators will be done based on the optimal results along with the parametric analysis of electricity-to-steam price variations.

2. POBC multi-objective optimisation model

A fuzzy multi-objective optimisation model is developed as an extension to the POBC retrofit study of Tan et al. (2020a) to consider alternative technologies for POME evaporation and simultaneous optimisation of four objective functions in addition to process route synthesis and POME management approach selections.

2.1 Problem statement

The optimisation problem can be formulated as below:

- Given a set of potential technologies *p* and resources *i* for palm oil mill and refinery processes including alternatives for POME evaporators.
- Given the economic data (product and resource pricing, unit operating cost, capital cost for advanced technologies), operating data for milling, refining and evaporation technologies (process capacity, resource and utility consumption, product yield) and environmental data (factors for WFP and GHG emission), fuzzy limits for EP, net energy, GHG balance and WFP that are obtained from single-objective optimal results.
- Fuzzy limits are used to describe the upper and lower satisfactory degree between 0 and 1 by formulating linear membership functions known as fuzzy constraints.
- The optimisation aim is to obtain the optimum POBC flowsheet for POM retrofit including process configuration and product portfolio by trading off all objectives via fuzzy optimisation approach towards maximising the value of aggregate degree for satisfying all fuzzy limits.

2.2 Model formulation

A mixed-integer linear programming (MILP) mathematical model is extended from the general formulation in the work of Tan et al. (2020b) including resource balance, material balances around the process, constraints for capacity and EP objective function. The net energy denoted as $EGBAL$ is defined as the surplus self-generated electricity on-site after meeting the POBC energy demand and should be maximised to reduce fossil fuel-based energy. A positive value of $EGBAL$ represents excess energy while a negative value indicates the required amount of electricity from external grid. The value of $EGBAL$ is given as the summation of excess biomass or biogas converted-electricity ($EXCESSELEC$) and amount of electricity sold to the grid ($PRO_{i=32}$) with total external electricity demand ($EXELEC$) deducted according to Eq(1).

$$EGBAL = PRO_{i=32} + EXCESSELEC - EXELEC \tag{1}$$

The net GHG balance in POBC ($GHGBAL$) is one of the optimisation criteria to be minimised in this study to combat climate change. $GHGBAL$ accounts for the GHG emissions from external resources ($RGHG$) and all installed processes ($TPGHG$) given in Eq(2). $MAT_{i,p}$ and $SGRES_{i,p}$ define the amount of feed and output resource *i* in process *p*. As binary indicators, $GHGRef_{i,p}$ identifies intermediate materials that emit GHG and $GHGind_i$ defines the resources that will contribute to positive or negative GHG contribution in Eq(3) and Eq(4). For example, selling on-grid electricity can reduce GHG footprint by replacing fossil fuel-based grid power.

$$GHGBAL = TPGHG + RGHG \tag{2}$$

$$TPGHG = \sum_i GHGRef_{i,p} \times MAT_{i,p} + \sum_i GHGRef_{i,p} \times SGRES_{i,p} \tag{3}$$

$$RGHG = \sum_i GHGind_i \times EXRES_i - (GHGind_{i=32} \times PRO_{i=32}) + (GHGind_{i=31} \times EXELEC) \tag{4}$$

The total WFP of POBC ($TWFP$) is minimised to reduce freshwater usage and water pollution impacts. $TWFP$ consists of blue WFP and grey WFP in Eq(5). The blue WFP is defined as the external water demand ($EXRES_{i=24}$). The grey WFP is calculated as the capacity to assimilate the amount of effluent generated (EFF) based on the given discharge concentrations (C^{eff}, C^{act}, C^{max}, C^{nat}).

$$TWFP = EXRES_{i=24} + EFF(\frac{C^{eff} - C^{act}}{C^{max} - C^{nat}}) \tag{5}$$

The multi-objective POBC optimisation model is solved using fuzzy optimisation approach by maximising the overall degree of satisfaction, λ in Eq(6) with subject to fuzzy constraints formulated in Eq(7)-(11) from upper and lower limits obtained from mono-objective optimisations. The superscripts *U* and *L* denote the upper and lower limits of the objective variables.

$$\text{Maximise } \lambda \tag{6}$$

$$\frac{EP-EP^L}{EP^U-EP^L} \geq \lambda \tag{7}$$

$$\frac{EGBAL-EGBAL^L}{EGBAL^U-EGBAL^L} \geq \lambda \tag{8}$$

$$\frac{GHGBAL^U-GHGBAL}{GHGBAL^U-GHGBAL^L} \geq \lambda \tag{9}$$

$$\frac{TWFP^U-TWFP}{TWFP^U-TWFP^L} \geq \lambda \tag{10}$$

$$0 \leq \lambda \leq 1 \tag{11}$$

3. Case study

The developed MILP optimisation model is applied to the POBC case study adapted from the work of Tan et al. (2020a). A POM in Western Malaysia is to be retrofitted into a POBC and integrated with a nearby refinery located within 1 km. The mill operating 4,350 h/y is fed with 60 t/h self-harvested fresh fruit bunches (FFB) to produce CPO. CPO is then processed to obtain Refined, Bleached, Deodorised Palm Olein (RBDPOL), Refined, Bleached, Deodorised Palm Stearin (RBDPS) and Palm Fatty Acid Distillate (PFAD) via physical refining and fractionation processes in the palm oil refinery. For POBC retrofit, only methane mitigation strategies (biogas facilities, POME elimination and oil recovery technologies) are considered with capital investment (CAPEX) for operational life span of 15 y and capital recovery rate at 0.096. The existing POM process units are subjected to operating costs only in the POBC flowsheet. In this case study, MEE with four effects and single-effect MVR evaporation system are included as alternative technologies for POME evaporation. All possible process routes and technologies considered for the POBC retrofit case study is shown in Figure 1. The process and economic data for the technologies in the case study are adapted based on literature and information shared by industrial personnel. The tariff basis for low-pressure steam (LPS) and electricity is 15.8 USD/MW and 140 USD/MW for the Malaysia case study. The baseline study considers the retrofit of a conventional POM to include biogas facilities at maximum EP to show the potential improvements that could be achieved by POME elimination and POBC implementation. Five scenarios are analysed to demonstrate the flowsheet variations concerning different technology selection and optimisation objectives as indicated in Table 1.

Table 1: Summarised objective function and technology considerations for baseline study and five scenarios

Scenario	Baseline	1	2	3	4	5
Maximise EP	√	√	√	√		
Maximise net energy		√				√
Minimise WFP		√			√	
Minimise GHG emission		√				
Biogas facility	√					
POME elimination (MEE)		√	√		√	√
POME elimination (MVR)		√	√	√	√	√

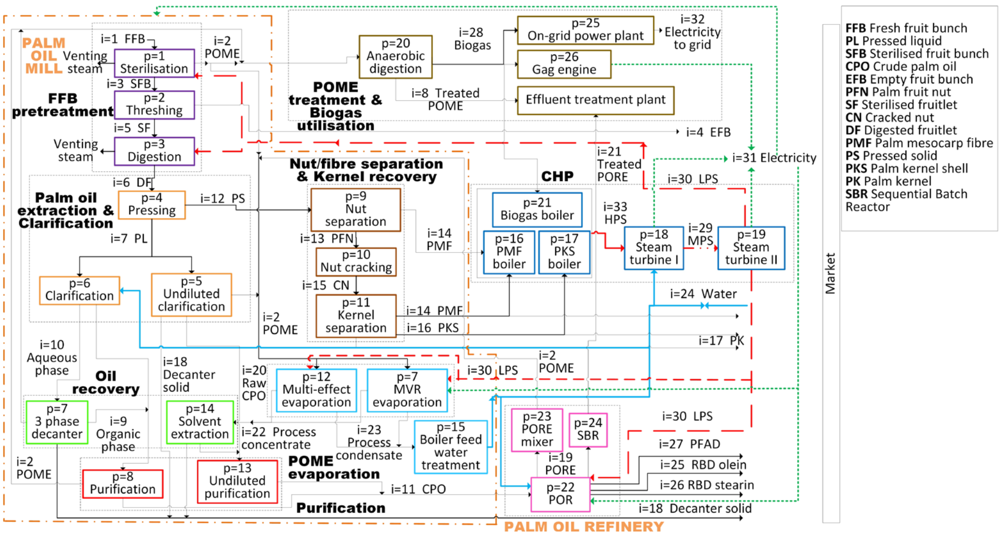

Figure 1: Potential configurations for POME evaporation in POBC

4. Results and discussion

The case study is solved by the developed MILP model and optimised in the General Algebraic Modelling System (GAMS) software (version 24.7.4) using the CPLEX solver (12.6.3.0).

4.1 Fuzzy multi-objective optimisation results

The optimal results for the six scenarios are summarised in Table 2. The baseline study represents the conventional POME-generating POM with biogas recovery while Scenarios 1-5 generates optimal POME-eliminated POBC. The results show that POME elimination and POBC retrofit could improve the EP, WFP and GHG balance of biogas utilising POM by 10 %, 47 % and 61 % at least. Although the baseline study contributes more net energy than POME eliminated-POBCs, the profitability and environmental impacts of biogas-to-energy conversion are not as favourable as POME evaporation. Scenario 1, 2 and 5 that evaporate POME via MEE still considered energy-efficient due to having excess on-site electricity. High electricity demand of MVR evaporator causes power deficit in the POBCs of Scenario 3 and 4 which implies grid dependency. The fuzzy optimal results in Scenario 1 are generated based on the fuzzy limits selected from individual EP, net energy, WFP and GHG balance optimised results. To improve the economic practicality of fuzzy solution, the EP upper limit is increased by 80 % of the difference between the largest and smallest EP results obtained. MEE is selected for the multi-objective POBC which is optimised based on the energy, economic and environmental trade-offs between MEE and MVR applications for POME evaporation. Among the single-objective POBC optimisation scenarios considering both evaporation technologies, MEE with lower CAPEX and electricity demand is chosen for POBCs concerning optimal EP, net energy and GHG balance. Single-effect MVR is only selected for WFP-minimised POBC to reduce water use for steam generation. Trade-offs in EP, GHG balance and net energy of POBC are observed with increased LPS import and PKS trading for reduction in boiler water consumption to attain maximum satisfaction between all objectives at 0.478. With MEE-based POME evaporation, the sustainable POBC in Scenario 1 is superior to the baseline study with 12 % EP increment, 61 % GHG reduction from biogas avoidance, 57 % WFP decrement from lower freshwater demand and effluent generation. The EP-oriented POBC with different evaporation system in Scenario 2 (MEE) and Scenario 3 (MVR) are compared to evaluate the performance of both technologies.

Steam economy is calculated as the amount of water evaporated per steam consumption, which reflects the thermal efficiency of evaporation system. Although MVR evaporator could achieve 181 % and 64 % improvements in steam economy and steam cost savings compared to MEE, its extensive electrical requirement could not be satisfied by self-generated utility due to insufficient biomass. The higher CAPEX and electrical charges also reduce the economic favourability of MVR-based POME evaporation.

Table 2: Summarised optimal results for six scenarios

Scenario	Baseline	1	2	3	4	5
λ	-	0.478	-	-	-	-
EP (M USD/y)	36.84	41.13	41.17	40.56	40.42	41.14
EGBAL (MWh)	1.174	0.502	0.609	-0.285	-1.08	0.919
GHGBAL (kgCO_2eq/h)	736.08	288.93	19.42	176.37	872.73	21.42
TWFP (t/h)	43.33	18.70	19.75	22.80	14.99	22.80
POME evaporation system	-	MEE	MEE	MVR	MVR	MEE
PKS sold (t/h)	3.56	1.18	0.88	0	2.25	0
Electricity cost for evaporation (M USD/y)	-	0	0	0.833	0.833	0
Steam cost for evaporation (M USD/y)	-	0.285	0.285	0.102	0.102	0.285
Steam economy (t water evaporated/t LPS consumed)	-	3.41	3.41	9.58	9.58	3.41
CAPEX (M USD)	4.54	1.86	1.86	2.19	2.19	1.86

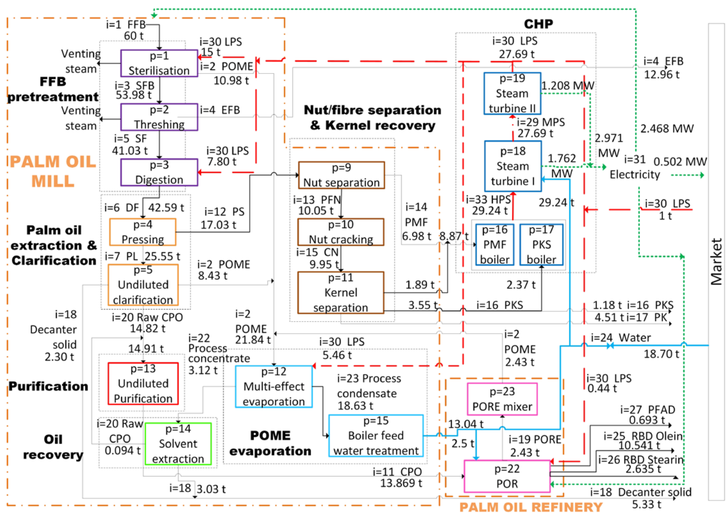

Figure 2: Optimal POBC flowsheet for Scenario 1

4.2 Parametric analysis on electricity-steam (ETS) price ratio

For countries with different electricity and steam prices, the variations in price ratios between steam and electricity may alter the economic favourability of MEE and MVR evaporators. Figure 3a illustrates the impacts of changing electricity-to-steam (ETS) price ratio on the maximum λ and EP achieved for POBC optimisation. The basis of ETS price ratio for the Malaysia case study in Section 3 is calculated as 8.872 with electricity tariff over steam price. The blue line depicts the trend for manipulating electricity price at fixed steam price of case study while the orange line represents steam price adjustments to obtain different ETS price ratios at fixed electricity tariff. No changes are observed in Figure 3a on the fuzzy degree of satisfaction for optimised POBC with electricity tariff variations. In contrast, the maximum value of λ increased with the ETS price ratio when steam price decreases, until it reaches the critical point of ETS ratio at 4.75 and turns into constant. This is because high steam price increased POBC's operating cost significantly in thermal processes such as sterilisation, resulting in low EP which drags the λ down before critical point. The grey line describes the effects of ETS price ratio variation on maximum EP of POBC. In this analysis, the POBC is optimised with the objective function of maximum EP only. The graph shows the changes in evaporator selection from MEE to MVR when the price ratio drops from 8.87 to 1.27 with electricity tariff reduction. Beyond the critical point at 1.27, the EP of MVR implemented POBCs continues to increase with further reduction in electricity price. This implies that MVR incorporation in POME-eliminated POBC is economically favourable for ETS price ratio at 1.27 and below. To evaluate the specific impact of ETS price ratio changes on MVR evaporator, Figure 3b is generated from the results of EP-maximised POBC with MVR investment. The benefit-cost ratio (BCR) is used to determine whether the steam cost savings of the MVR evaporator from MEE is favourable compared to its additional electricity cost. Positive log BCRs imply economically feasible scenarios where the benefit outweighs the associated cost. Based on Figure 3b, the economic feasibility of MVR evaporation is only viable with an ETS price ratio lower than 1.9 for fixed steam tariff and increases with further price ratio decrement.

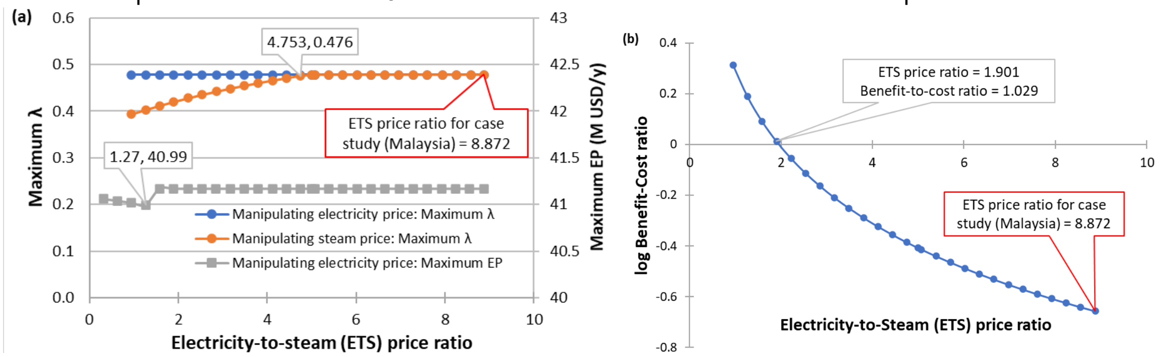

Figure 3: Graph of (a) maximum λ and EP, and (b) log (benefit-cost ratio) against ETS price ratio

5. Conclusions

A fuzzy MILP optimisation model is developed for POBC flowsheet design concerning four optimisation objectives. Besides POME management and process route selections for POBC retrofit, the model is capable of aiding decision-makers in determining the optimum POME evaporation technology from MEE and MVR alternatives. MEE is chosen in the fuzzy POBC which trade-offs EP, net energy and GHG balance for WFP reduction to achieve 0.478 of λ, showing 12 %, 61 % and 57 % improvements in EP, GHG and water footprints compared to biogas recovering POM. MVR evaporator contributes 64 % of steam savings with undesirable electrical demand. ETS price analysis suggests critical improvements in economic feasibility of MVR-implemented POBC and MVR evaporator for POME dewatering at price ratio below 1.27 and 1.9 with current steam price. Vapour recompression in multi-effect POME evaporation will be considered in the future.

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