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Multi-objective Optimization for Cascade Utilization of Palm Waste in Malaysia using Augmented ε-constraint Method

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Palm waste has gained traction in the energy industry due to its wide availability. Despite its vast potential as feedstock for downstream industries, palm wastes are still inadequately utilized in Malaysia. Conventional disposal practices of palm waste are economically inefficient and environmentally unfavorable. This study adopted the multi-objective linear programming approach to design the optimal palm waste utilization pathway in Malaysia using the General Algebraic Modeling System, which maximizes profit and minimizes greenhouse gas (GHG) emissions. The 5[th] Pareto solution (composting: 79.31 %; anaerobic digestion (AD): 10.05 %; pelletizing: 0.35 %; briquetting: 0.37 %; biomass combined heat and power: 9.47 %; dried long fiber production: 0.42 %; carbonization: 0.02 %) that has a net profit of 5.02 x 10^9 MYR/y and net GHG emissions of -1.6 x 10^7 t CO_2-eq/y is the most viable as it satisfies both objectives to a degree of satisfaction of 0.77. The 1[st] and 2[nd] Pareto solution allocates 8.74 x 10^9 t of solid palm wastes to electricity and heat generation and can achieve the renewable energy target under the biomass category set by the Malaysian government. 3.72 x 10^7 – 5.16 x 10^7 t of palm oil mill effluent allocated to AD in the 9[th], 10[th], and 11[th] Pareto solutions can achieve the RE target under the biogas category. This study provides insights on the best allocation of palm waste for the stakeholders to devise a proper strategy for effective palm waste utilization that is economically and environmentally viable.

1. Introduction

As the world's second-largest oil palm producer, the Malaysian palm oil industry produces more than 1 x 10^8 t of palm wastes annually; unfortunately, most of the wastes are not utilized or managed properly (Hamzah et al., 2019). Current practices like open dumping of empty fruit bunches (EFB) and open pond treatment of palm oil mill effluent (POME) are economically undesirable and generate a huge amount of greenhouse gases (GHG).
Abdulrazik et al. (2017) adopted the fuzzy optimization method to maximize the economic potential of the EFB supply chain in Peninsular Malaysia. Many of the processing technologies (i.e., biodiesel production, formaldehyde production) in the study were not proven to be commercially feasible for EFB and its derivatives. Theo et al. (2017) adopted the fuzzy optimization approach to optimize the palm biomass and POME utilization pathway using a discontinuous non-linear programming model. The model aimed to maximize the annual worth of each palm oil mill. Shukery et al. (2016) optimized the palm waste pathway in an oil palm eco-industrial park to maximize economic performance while minimizing the GHG emissions and biochemical oxygen demand of wastewater in the eco-industrial park. The study only considers the baseline GHG emissions from the palm wastes unused, while the GHG emissions from the processing stage were omitted. Tan et al. (2020a) presented an optimal integrated palm oil-based complex considering economic potential, electricity generation, net GHG emissions, land footprint, and water footprint. Tey et al. (2021) adopted the fuzzy optimization method to synthesize a sustainable integrated biorefinery; the study showed that it is possible to maintain the sustainability elements with minimal compromise on economic performance. Hafyan et al. (2020) also optimized the

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integrated biorefinery of empty fruit bunch by considering the economic, environmental, and safety performance. Kermani et al. (2017) presented a techno-economic and environmental optimization of palm-based biorefinery in Brazil; it revealed that system expansion, recovering mill residues, and producing value-added products can improve the environmental performance. Most of the studies did not consider the net GHG emissions of their results compared to the baseline case, which is essential since one may not know if utilizing palm wastes according to the studies' configurations brings about a net GHG emissions reduction or emits more GHGs.
This study designs the optimal cascaded utilization pathway of palm waste from the economic and environmental perspective using the General Algebraic Modeling System (GAMS) (GAMS, 2019). The novelty of this study is producing a set of Pareto solutions using the augmented ε-constraint method to better demonstrate the trade-offs between the two opposing objectives as opposed to the single solution obtained from fuzzy optimization. This study also incorporates the baseline emissions of the palm wastes in the model as avoided emissions when determining the net GHG emissions. The solution presents the actual GHG emissions reduction achievable when subjecting them to the optimal utilization pathway.

2. Methodology

2.1 Superstructure and data collection

This study adopts the augmented ε-constraint method in a multi-objective linear programming approach to design the optimal cascaded palm waste utilization pathway that simultaneously maximizes profit and minimizes GHG emissions (Ooi and Woon, 2021). The model determines the best allocation of four types of palm wastes: palm oil mill effluent (POME), empty fruit bunch (EFB), palm kernel shell (PKS), and palm mesocarp fiber (PMF) to eight existing processing technologies commonly adopted in Malaysia. Figure 1 shows the superstructure of this model. Table 1 shows the capital cost, operation and maintenance (O&M) cost, and the emission factor of the processing technologies.

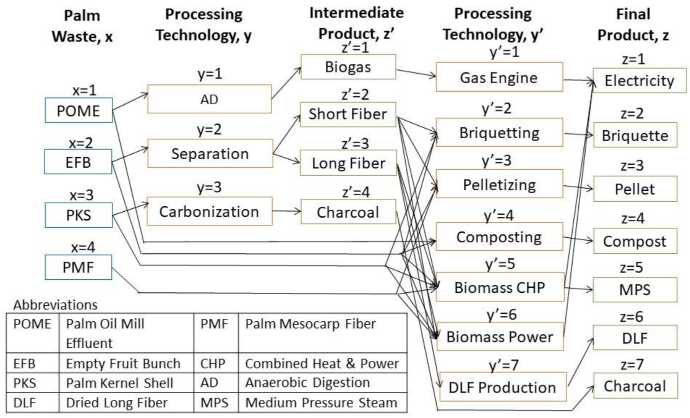

Figure 1: Simplified superstructure of the model

Table 1: Capital cost, operation and maintenance cost, and the emission factor of the processing technologies

	Separation	Pelletizing	DLF production	Biomass power	Biomass CHP	AD	Briquetting	Carbonization	Composting
Capital cost (MYR)	9.40×10^6	1.24×10^7	2.20×10^6	4.28×10^7	2.56×10^8	1.80×10^7	2.72×10^6	5.60×10^4	1.30×10^6
O&M cost (MYR/y)	4.43×10^6	4.99×10^6	1.90×10^5	1.30×10^7	6.78×10^6	7.14×10^5	3.82×10^6	1.51×10^5	2.13×10^6
Emission factor[1]	4.10×10^{-3}	1.25×10^{-2}	4.10×10^{-3}	5.29×10^{-5}	5.29×10^{-5}	2.30×10^{-3}	1.25×10^{-2}	0.58	1.90×10^{-2}

[1]The emission factor unit for separation, pelletizing, DLF production, briquetting, carbonization, and composting is t CO_2-eq/t product, while for biomass power, biomass CHP, and AD is t CO_2-eq/kWh.

The model has a study period of one year. The major assumptions made in this model are as follows:

- An annual discount rate of 4 % and operating lifespan of 20 y for all the processing plants
- The average distance between palm oil mills and processing plants, and from processing plants to demand centre/port is 100 km, with a truck capacity of 22 t and 8×10^{-4} t CO_2-eq/km (Reeb et al., 2014)
- No land-use change occurred and all processing plants operate for 4,350 h/y (Tan et al., 2020b)

- Pellets, briquettes, charcoal, compost, and dried long fibers are shipped to Nagoya, Japan (6,971 km) with the average deep-sea container vessel. It has an emission factor of 8.4×10^{-6} t CO_2-eq/(t·km) (ECTA, 2011)

2.2 Model development

The first objective function of this model is profit maximization, as expressed in Eq(1), where the revenue from the final products (REV) is subtracted by annualized capital expenditure ($COST_{\mathrm{CAP}}$), operation and maintenance cost ($COST_{\mathrm{O\&M}}$), and transportation cost ($COST_{\mathrm{TRANS}}$). Eq(2) to Eq(5) show the mentioned components.

$$\mathrm{Max}(profit) = REV - COST_{\mathrm{CAP}} - COST_{\mathrm{O\&M}} - COST_{\mathrm{TRANS}} \quad (1)$$

$$COST_{\mathrm{CAP}} = \Sigma_y (\mathrm{UCAP}_y \; x \; n_y) \quad (2)$$

$$COST_{\mathrm{O\&M}} = \Sigma_y (\mathrm{UO\&M}_y \; x \; n_y) \quad (3)$$

$$COST_{\mathrm{TRANS}} = 2 \; x \; [\Sigma_x \Sigma_y (\mathrm{UTRANS} \; x \; \mathrm{d}_{x,y} \; x \; a_{x,y}) + \Sigma_y \Sigma_z (\mathrm{UTRANS} \; \mathrm{x} \; \mathrm{d}_{y,z} \; x \; a_{y,z})]/\mathrm{TCAP} \quad (4)$$

$$REV = \Sigma_y \Sigma_z (\mathrm{MARPRICE}_z \; x \; a_{y,z}) \quad (5)$$

where UCAP_y: annualized capital expenditure per unit of y^{th} processing facility; $\mathrm{UO\&M}_y$: O&M cost per unit of y^{th} processing facility; n_y: number of y^{th} processing facility; UTRANS: transportation cost per unit distance; $\mathrm{d}_{x,y}$: distance from mill producing x^{th} palm waste to y^{th} processing facility; $\mathrm{d}_{y,z}$: distance from y^{th} processing facility to market for z^{th} product; TCAP: transportation capacity; $\mathrm{MARPRICE}_z$: market price of z^{th} product; $a_{x,y}$: amount of x^{th} palm waste allocated to y^{th} processing facility; $a_{y,z}$: amount of z^{th} product from y^{th} processing facility.

Eq(6) describes the second objective function, which is the minimization of GHG emissions. The net GHG emissions are calculated by summing the GHG emissions from palm waste processing (EM_{PRO}) and transportation (EM_{TRANS}), subtracted by the avoided emissions (EM_{AV}). Eq(7), Eq(8), and Eq(9) represent the computation of EM_{PRO}, EM_{TRANS}, and EM_{AV}.

$$\mathrm{Min}(ghg) = EM_{\mathrm{PRO}} + EM_{\mathrm{TRANS}} - EM_{\mathrm{AV}} \quad (6)$$

$$EM_{\mathrm{PRO}} = \Sigma_y \Sigma_z (\mathrm{PROEF}_{y,z} \; \mathrm{x} \; a_{y,z}) \quad (7)$$

$$EM_{\mathrm{TRANS}} = 2 \; \mathrm{x} \; [\Sigma_x \Sigma_y (\mathrm{UETRANS} \; \mathrm{x} \; \mathrm{d}_{x,y} \; \mathrm{x} \; a_{x,y}) + \Sigma_y \Sigma_z (\mathrm{UETRANS} \; \mathrm{x} \; \mathrm{d}_{y,z} \; \mathrm{x} \; a_{y,z})]/\mathrm{TCAP} \quad (8)$$

$$EM_{\mathrm{AV}} = (ELEC_{\mathrm{BIOMASS}} + ELEC_{\mathrm{BIOGAS}}) \; \mathrm{x} \; \mathrm{UEELEC} + \Sigma_x \Sigma_y (\mathrm{UEBASELINE}_x \; \mathrm{x} \; a_{x,y}) \quad (9)$$

where $\mathrm{PROEF}_{y,z}$: emission factor of z^{th} product at y^{th} processing facility; UETRANS: emissions of transportation per unit distance (km); $ELEC_{\mathrm{BIOMASS}}$: biomass-derived electricity; $ELEC_{\mathrm{BIOGAS}}$: biogas-derived electricity; UEELEC: national grid emissions intensity; $\mathrm{UEBASELINE}_x$: baseline emissions of x^{th} palm waste.

The current practice (baseline) is to discard the EFB to a landfill, while 80 % of the POME are treated using the open anaerobic ponding system. $\mathrm{UEBASELINE}_x$ due to natural decay of EFB in a dumpsite is computed using "Methodological tool: emissions from solid waste disposal sites" (CDM, 2019a); $\mathrm{UEBASELINE}_x$ of POME from open anaerobic ponds is calculated using "Small-scale methodology: methane recovery in wastewater treatment" by Clean Development Mechanism (CDM) (CDM, 2019b).

The model is subjected to six constraints. Eq(10) denotes the supply constraint of the model, in which the palm waste allocated does not exceed its availability. Eq(11) ensures that the palm waste processed by a processing facility is well within its processing capacity; Eq(12) emphasizes that the model must fulfill the demands for the products in the market. Eq(13) is the mass balance constraint. Eq(14) and Eq(15) ensure that sufficient biomass- and biogas-derived electricity are injected into the grid to meet the allocated Feed-in-Tariff (FiT) quota for biomass and biogas categories, while Eq(16) and Eq(17) shows the details of biomass- and biogas-derived electricity. Eq(18) describes the energy balance constraint, where the electricity and heat generated must be lower than the net calorific value of the palm wastes.

$$\mathrm{w}_x \geq \Sigma_y a_{x,y} \quad \forall x \quad (10)$$

$$n_y \; \mathrm{x} \; \mathrm{CAP}_y \geq \Sigma_x a_{x,y} \quad \forall y \quad (11)$$

$$\Sigma_y a_{y,z} \geq \mathrm{DEMAND}_z \quad \forall z \quad (12)$$

$$a_{y,z} = \mathrm{CONV}_{x,y,z} \; \mathrm{x} \; a_{x,y} \quad \forall x, y, z \quad (13)$$

$$ELEC_{BIOMASS} \geq FiTBM_{allocated} \times AOH \quad (14)$$

$$ELEC_{BIOGAS} \geq FiTBG_{allocated} \times AOH \quad (15)$$

$$ELEC_{BIOMASS} = \Sigma_x \Sigma_y (BMELECCF_{x,y} \times a_{x,y}) \quad (16)$$

$$ELEC_{BIOGAS} = \Sigma_x \Sigma_y (BGELECCF_{x,y} \times a_{x,y}) \quad (17)$$

$$ELEC_{BIOMASS} + ELEC_{BIOGAS} + \Sigma_x \Sigma_y H_{x,y} \leq \Sigma_x (\Sigma_y a_{x,y} \times CV_x) \quad (18)$$

where w_x: x^{th} type of palm waste; CAP_y: capacity of y^{th} processing facility; $DEMAND_z$: demand for z^{th} product; $CONV_{x,y,z}$: conversion factor of x^{th} palm waste to z^{th} product at y^{th} processing facility; $FiTBM_{allocated}$: FiT quota allocated for biomass-electricity; AOH: annual operating hours; $FiTBG_{allocated}$: FiT quota allocated for biogas-electricity; $BMELECCF_{x,y}$: biomass-derived electricity generation factor; $BGELECCF_{x,y}$: biogas-derived electricity generation factor; $H_{x,y}$: heat energy of steam produced; CV_x: net calorific value of x^{th} palm waste.

3. Results and discussions

Figure 2 shows the set of Pareto optimal solutions of the model, illustrating the trade-offs between two conflicting objective functions: maximizing profit and minimizing net GHG emissions. All 11 optimal solutions are equally good with different trade-offs between environmental and economic benefits. It applies the lexicographic optimization method on the profit objective function while expressing the net GHG emissions function as a constraint, generating a comprehensive efficient set. The baseline emissions are the emissions from the palm wastes if they are handled using the conventional methods, which are open ponding treatment of POME and open dumping of EFB in landfills; utilizing the palm wastes results in avoided baseline emissions. All solutions obtained a negative net GHG emissions value due to the high baseline emissions (1.68 x 10^7 t CO_2-eq/y), indicating that all the optimal solutions in this study assure a net GHG emissions reduction.

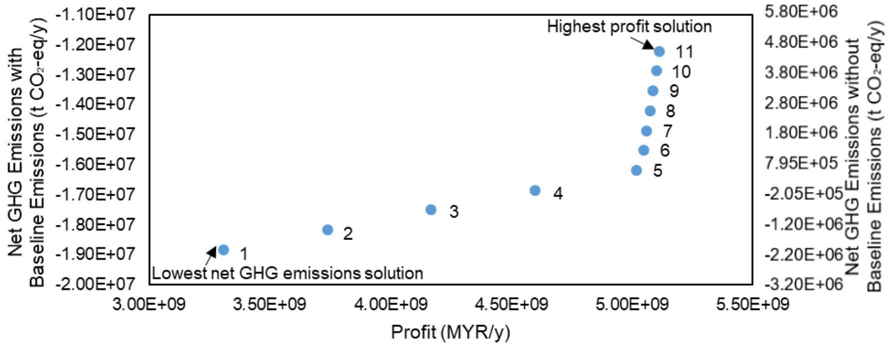

Figure 2: The Pareto frontier of Pareto optimal solutions

The net GHG emissions increase with the increasing profit, and the Pareto frontier showed a near-linear relationship in two regions (from 1st to 5th solution; 6th to 11th solution). The 1st solution has the lowest net GHG emissions, whereas the 11th solution has the highest profit. The 1st and the 11th solution can achieve a net emissions reduction of 1.88 x 10^7 t CO_2-eq/y and 1.22 x 10^7 t CO_2-eq/y, contributing to 8.25 % and 5.35 % of the GHG emissions reduction required to meet the emissions reduction target of 45 % by 2030 (Paris Agreement). From the 6th to 11th solution, the net GHG emissions increase substantially (27.94 %) while resulting in only a 1.85 % rise in net profit. Stakeholders should not sacrifice such huge emissions reduction for a relatively small profit gain by choosing the higher profit solutions. The 5th solution (profit: 5.02 x 10^9 MYR/y; net GHG emissions: -1.6 x 10^7 t CO_2-eq/y) appears to be the most viable, as it maintains a high-profit level without sacrificing the net GHG emissions reduction by too much. From a mathematical point of view, the 5th solution satisfies both objective functions simultaneously to a degree of satisfaction of 0.77, which is the highest amongst the other optimal solutions. Employing the palm waste allocation configurations of the 5th Pareto optimal solution (composting: 79.31 %; AD: 10.05 %; pelletizing: 0.35 %; briquetting: 0.37 %; biomass CHP: 9.47 %; DLF production: 0.42 %; carbonization: 0.02 %) is strongly recommended.
Figure 3 illustrates the palm waste allocation configuration to different processing technologies of the 11 Pareto solutions. Figures 2 and 3 together provide the stakeholders with a bigger picture for the decision-making process and better understand the relationship between GHG emissions, profit, and palm waste processing

technologies. For the first five solutions, the palm wastes allocated to all processing technologies remain the same, except for biomass power (power generation only) and biomass CHP (heat and power generation). Palm waste allocated to biomass power is gradually diverted to biomass CHP when the solution shifts from the 1st solution to the 5th solution for higher profit gain, yielding a linear relationship as shown in Figure 2. Biomass power utilizes a condensing turbine that maximizes electricity generation, but the overall efficiency is lower. CHP has higher overall efficiency (thermal + electricity) due to the utilization of heat that is otherwise wasted in a condensing turbine; the economic performance of CHP is better than that of power-only generation technology (EPA, 2021). More palm wastes are allocated for biomass power generation when shifting towards the lowest net GHG emissions solution due to the higher amount of electricity displaced from the grid, creating higher avoided GHG emissions. The 1st Pareto optimal solution (lowest net GHG emissions solution) allocates 31 % of the solid palm wastes for biomass power generation, achieving an electricity generating capacity of 1,830.46 MW (based on 4,350 annual operating hours). It exceeds the national RE target for the biomass category (1,340 MW) by 36.60 %. The second solution also exceeds the mentioned target by 14.54 %, while the subsequent Pareto optimal solutions fall short of hitting the biomass RE target due to the gradual displacement of biomass power by biomass CHP. The model chooses the direct utilization of EFBs to produce pellets, briquettes, heat, and electricity for the first five Pareto optimal solutions without separating the long fibers from the short fibers. Although separating EFBs can yield short fibers and long fibers, which is the precursor of DLF that is of high market value, the separation process contributes to additional GHG emissions. If priority is given to net GHG emissions reduction instead of profitability, EFB should not undergo a separation process.

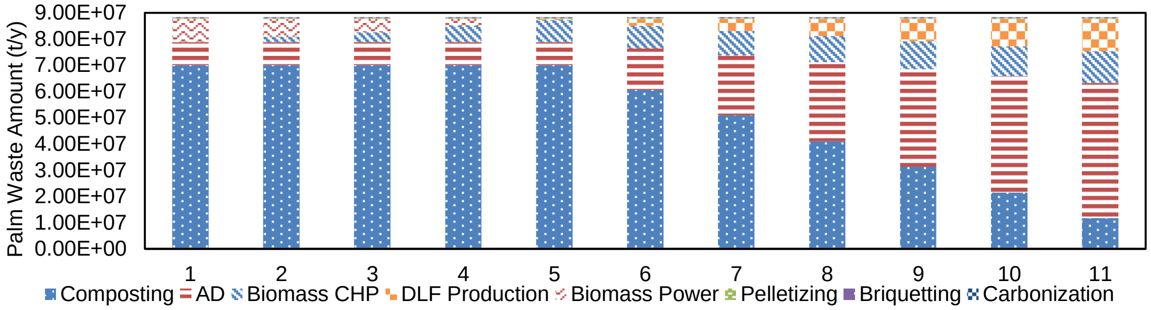

Figure 3: Configuration of the proposed palm waste allocation for each Pareto optimal solutions

The model favors utilizing POME for composting when priorities are given to minimizing net GHG emissions. More POME is subjected to AD for biogas-derived electricity generation when transiting towards higher profit solutions due to the lucrative price of electricity offered by Sustainable Energy Development Authority (SEDA) Malaysia. Given the national RE target under the biogas category of 410 MW set in the National Renewable Energy Policy and Action Plan, the 9th, 10th, and 11th solutions exceed the target by 13.56 % - 57.38 %. SEDA's current total capacity (installed + available capacity) was extremely limited mainly due to financial constraints, having only 203.51 MW and 304.49 MW under the biomass and biogas-electricity category (SEDA, 2021). It is essential to open up more slots for RE uptake if the country's budget allows since the results suggest that it is possible to achieve the RE target while having a net emissions reduction and maintaining high profitability.
The model allocates a minimal amount of palm waste to produce charcoal, pellet, and briquette, indicating that they are not as economical and environmentally friendly as composting and DLF production. Abdulrazik et al. (2017) showed that producing DLF has the highest profit. It is consistent with this study since the model allocates more EFB to DLF production when there is more emphasis on profitability. The combined effect of more palm wastes allotted to DLF production and AD, and the shrinking amount allocated to composting, lead to the steep rise in net GHG emissions observed for the 5th to 11th solution. The model allocates most of the PKS (97.55 %) and PMF (100 %) to heat and electricity generation; only a minor fraction of EFB (average: 6.30 %) is allotted for such purpose. It is because PKS and PMF have higher calorific value and better combustion characteristics, as stated in the work of Loh (2017). It also indicated that there are more environmentally and economically attractive alternatives to utilizing EFB for heat and power generation, such as composting and DLF production.

4. Conclusion

This study presents the quantitative value of net GHG emissions reduction and net profit achievable if palm waste is utilized efficiently. The results show that the current disposal practices are environmentally damaging, in which a net GHG emissions reduction is attainable as long as one starts to utilize the palm wastes according to the allocations in this study. It also shows that the 5th solution satisfies both objective functions to the highest degree (0.77) amongst all the alternatives; allocating palm wastes according to its allocation configuration (composting: 79.31 %; AD: 10.05 %; pelletizing: 0.35 %; briquetting: 0.37 %; biomass CHP: 9.47 %; DLF production: 0.42 %; carbonization: 0.02 %) is recommended. It is hoped that this study can serve as a reference for the stakeholders to design an effective palm waste utilization pathway in the palm-oil producing countries.

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